US010632313B2

(12) **United States Patent**
Juffer et al.

(10) **Patent No.: US 10,632,313 B2**
(45) **Date of Patent: Apr. 28, 2020**

(54) **SYSTEMS, DEVICES, AND METHODS FOR SETTING CARDIAC PACING PULSE PARAMETERS FOR A CARDIAC PACING DEVICE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 173 days.

(21) Appl. No.: **15/804,699**

(22) Filed: **Nov. 6, 2017**

(65) **Prior Publication Data**

US 2018/0126174 A1 May 10, 2018

Related U.S. Application Data

(60) Provisional application No. 62/419,731, filed on Nov. 9, 2016.

(51) **Int. Cl.**

A61N 1/37	(2006.01)
A61N 1/375	(2006.01)
A61N 1/372	(2006.01)
A61N 1/378	(2006.01)

(52) **U.S. Cl.**

CPC ***A61N 1/3712*** (2013.01); ***A61N 1/371*** (2013.01); ***A61N 1/378*** (2013.01); ***A61N 1/3756*** (2013.01); ***A61N 1/37247*** (2013.01); ***A61N 1/37512*** (2017.08); *A61N 1/3708* (2013.01)

(58) **Field of Classification Search**

CPC ... A61N 1/371; A61N 1/3712; A61N 1/37247

See application file for complete search history.

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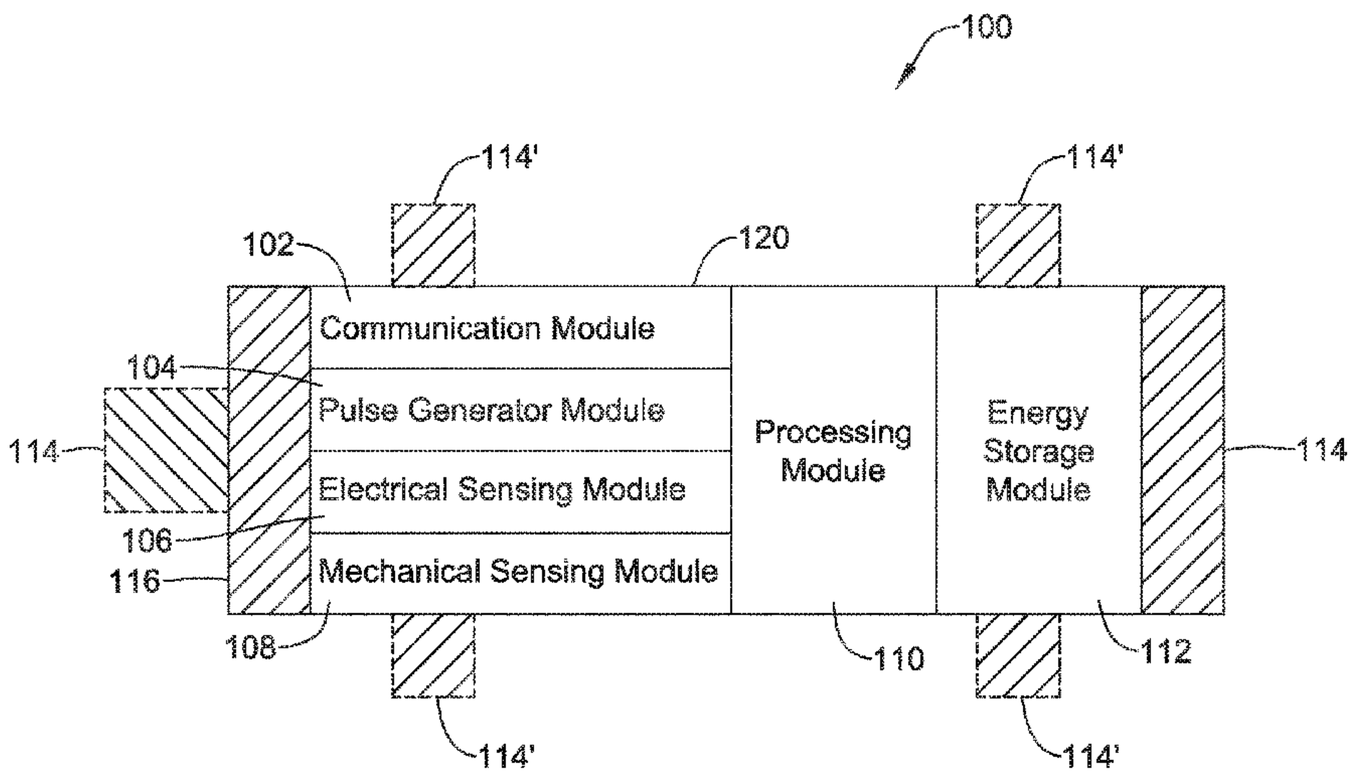
(57) **ABSTRACT**

Systems, devices, and methods for pacing a heart of a patient are disclosed. A device may include a leadless cardiac pacemaker (LCP) that includes a power supply, a pair of electrodes, and a controller operably connected to the electrodes and the power supply. The controller may identify a capture threshold by setting a pace amplitude at a power supply voltage of the power supply and deliver pacing stimulation pulses with different pulse widths to identify the capture threshold. The LCP may then deliver pacing stimulation pulses based, at least in part, on a pulse amplitude and pulse width associated with the capture threshold, and also adding a capture margin. In some cases, the pulse amplitude may change over time and the LCP may adjust a pulse width along a strength-duration curve to account for the pulse amplitude change and maintain a capture threshold and capture margin.

20 Claims, 12 Drawing Sheets



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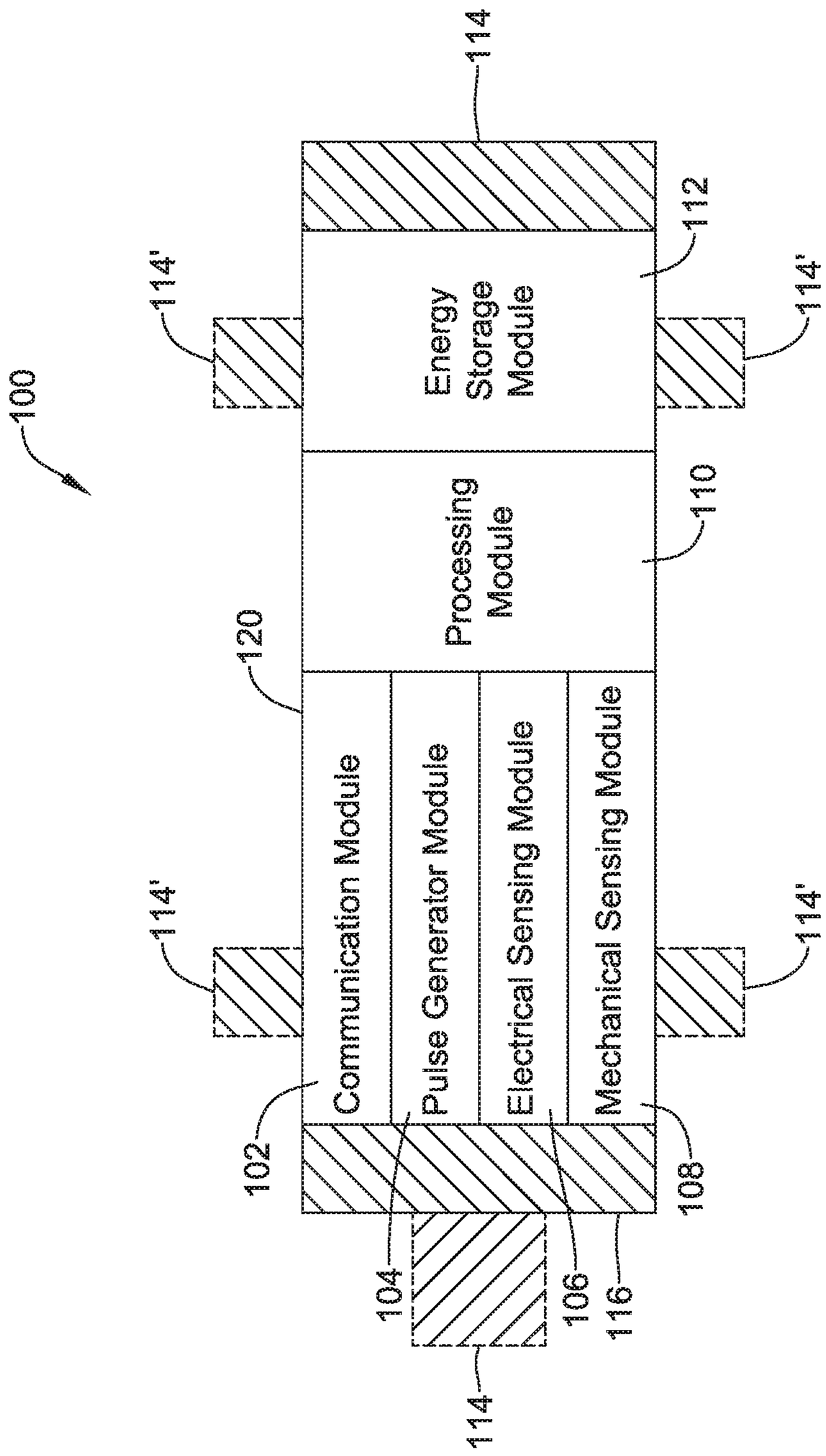
100
102
104
106
108
110
112
114
114'
116
120
Communication Module
Pulse Generator Module
Electrical Sensing Module
Mechanical Sensing Module
Processing Module
Energy Storage Module

Figure 1

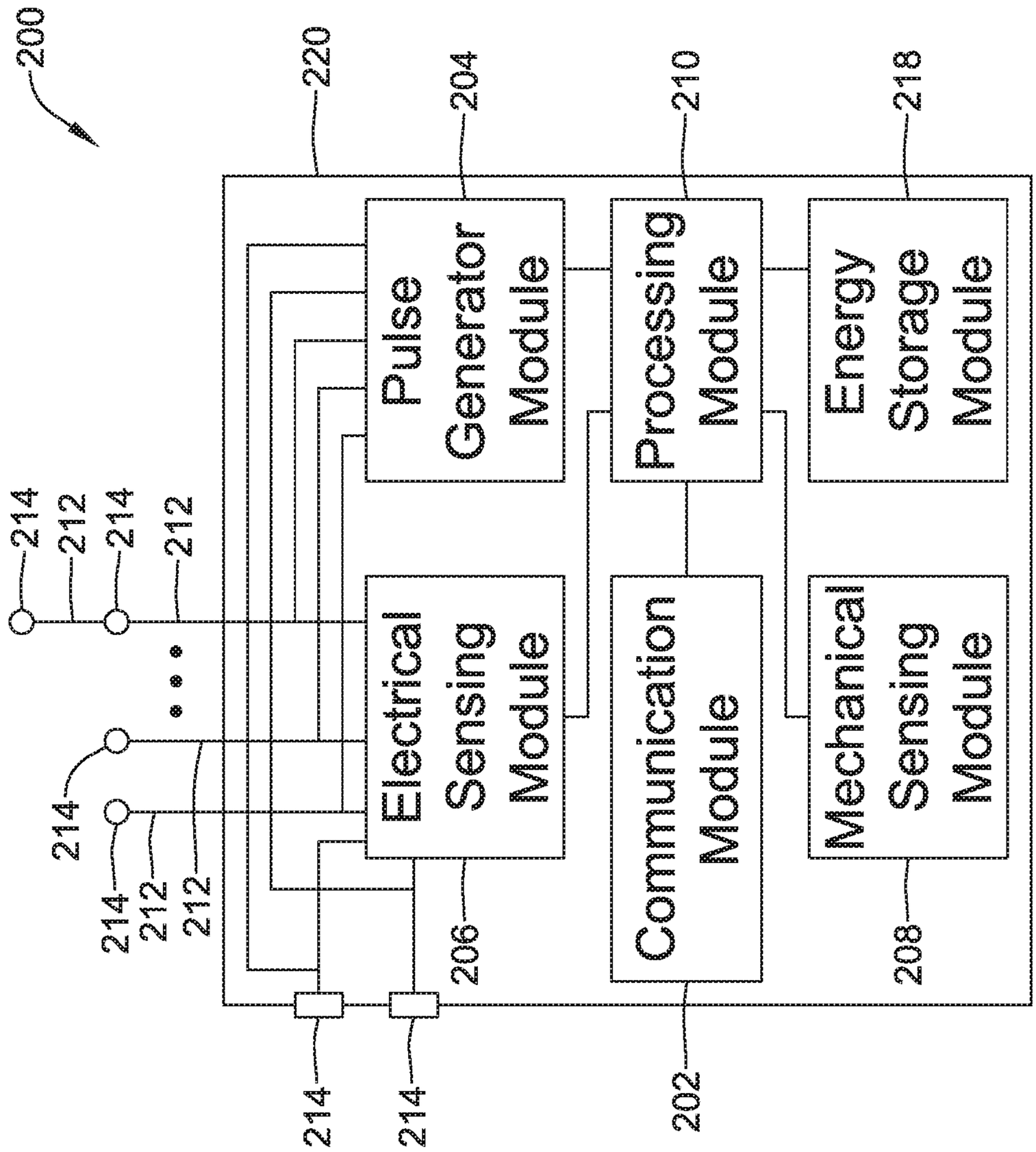
200
220
204
210
218
Pulse Generator Module
Processing Module
Energy Storage Module
Electrical Sensing Module
Communication Module
Mechanical Sensing Module
206
208
202
214
212

Figure 2

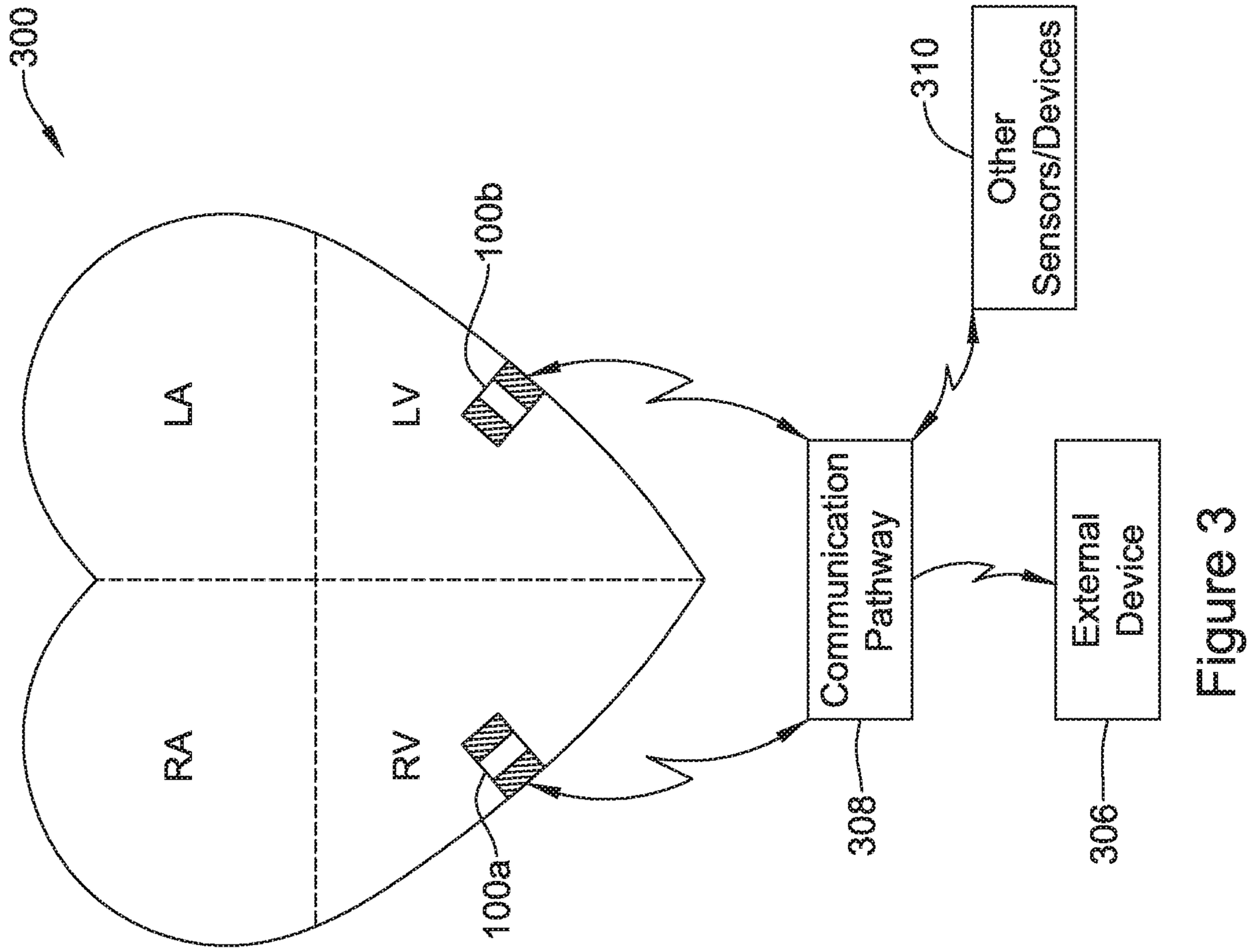
300
LA
LV
RA
RV
100b
100a
Other Sensors/Devices
310
Communication Pathway
308
External Device
306

Figure 3

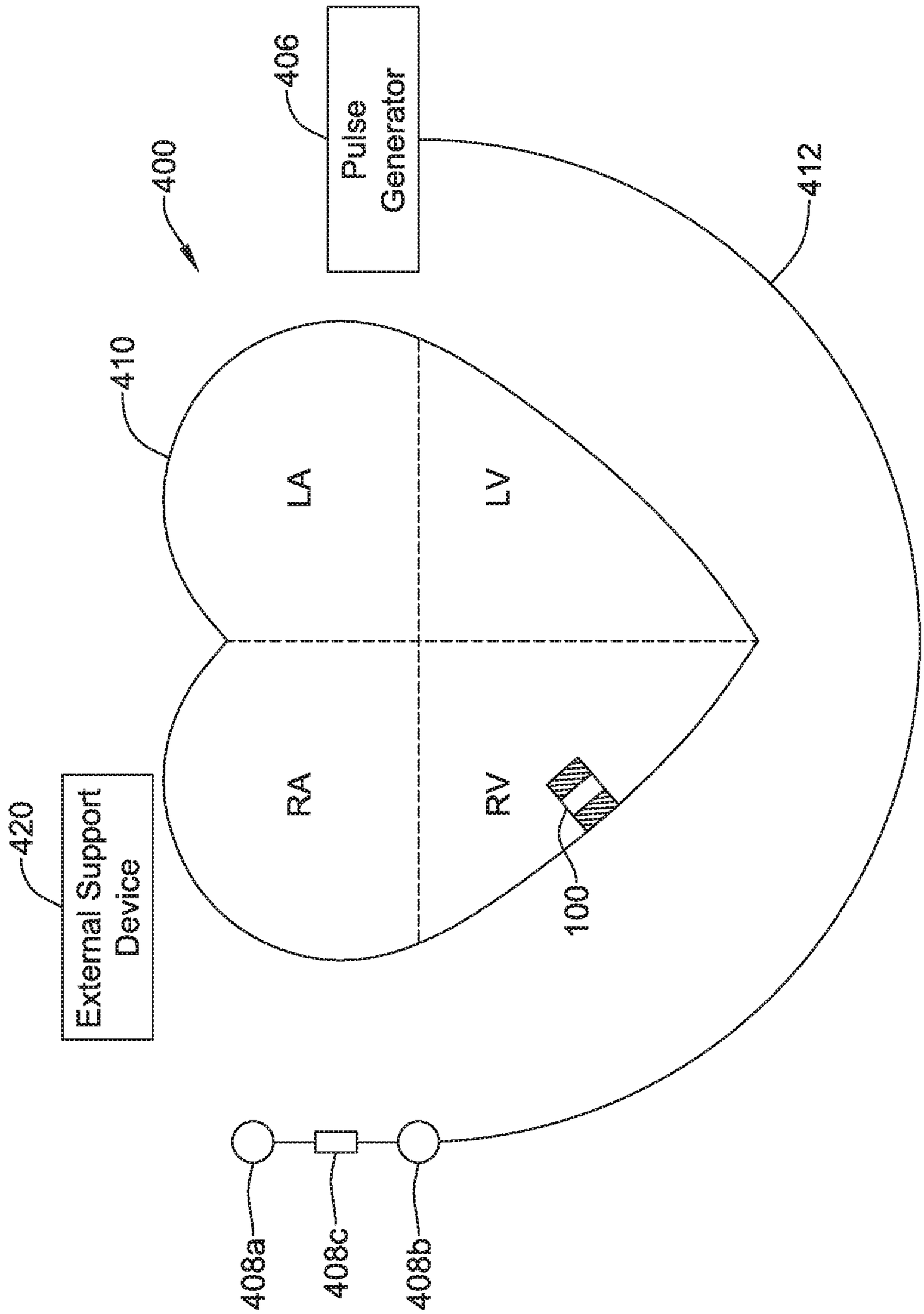
400
406
Pulse Generator
412
410
LA
LV
RA
RV
100
420
External Support Device
408a
408c
408b

Figure 4

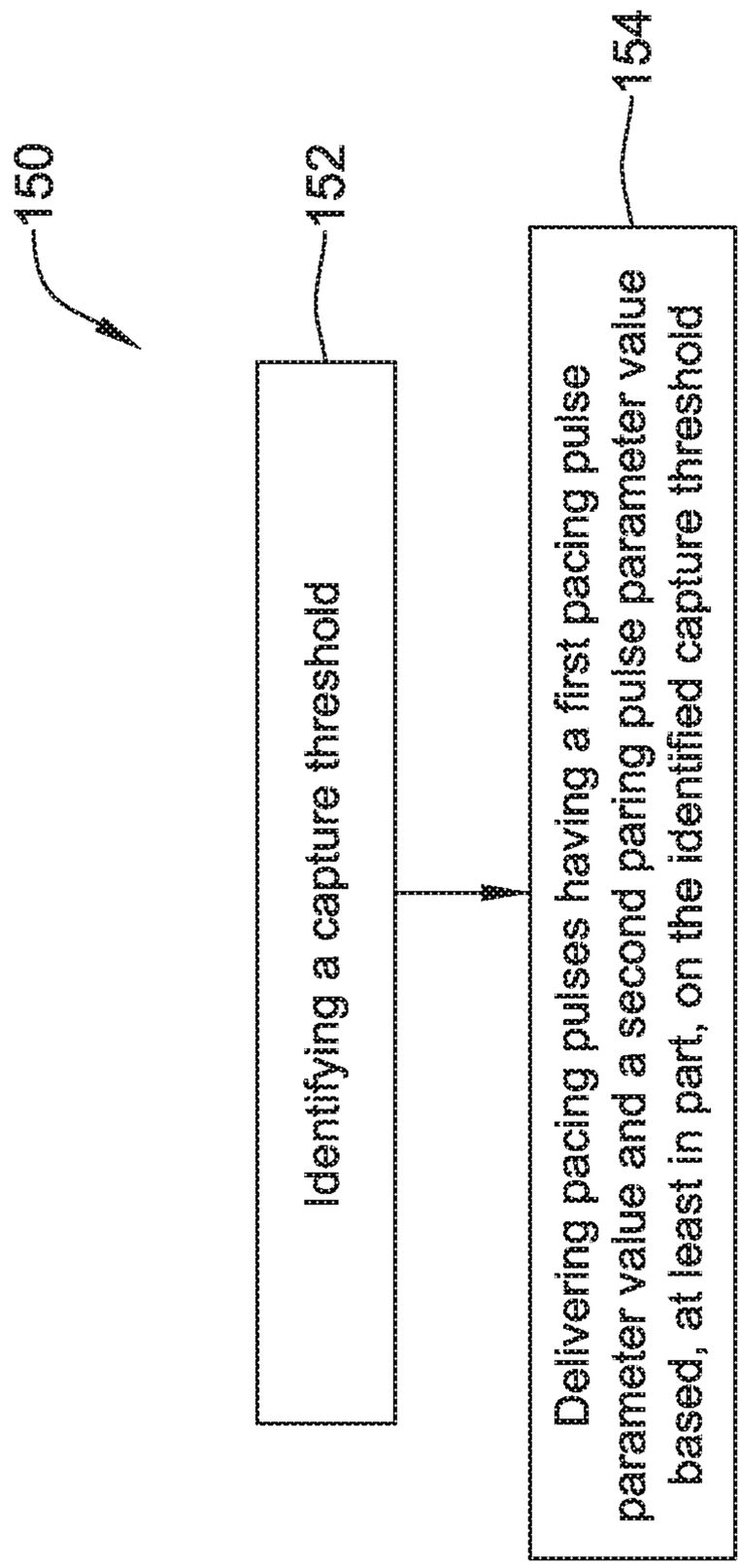
150
152
Identifying a capture threshold
154
Delivering pacing pulses having a first pacing pulse parameter value and a second paring pulse parameter value based, at least in part, on the identified capture threshold

FIG. 5

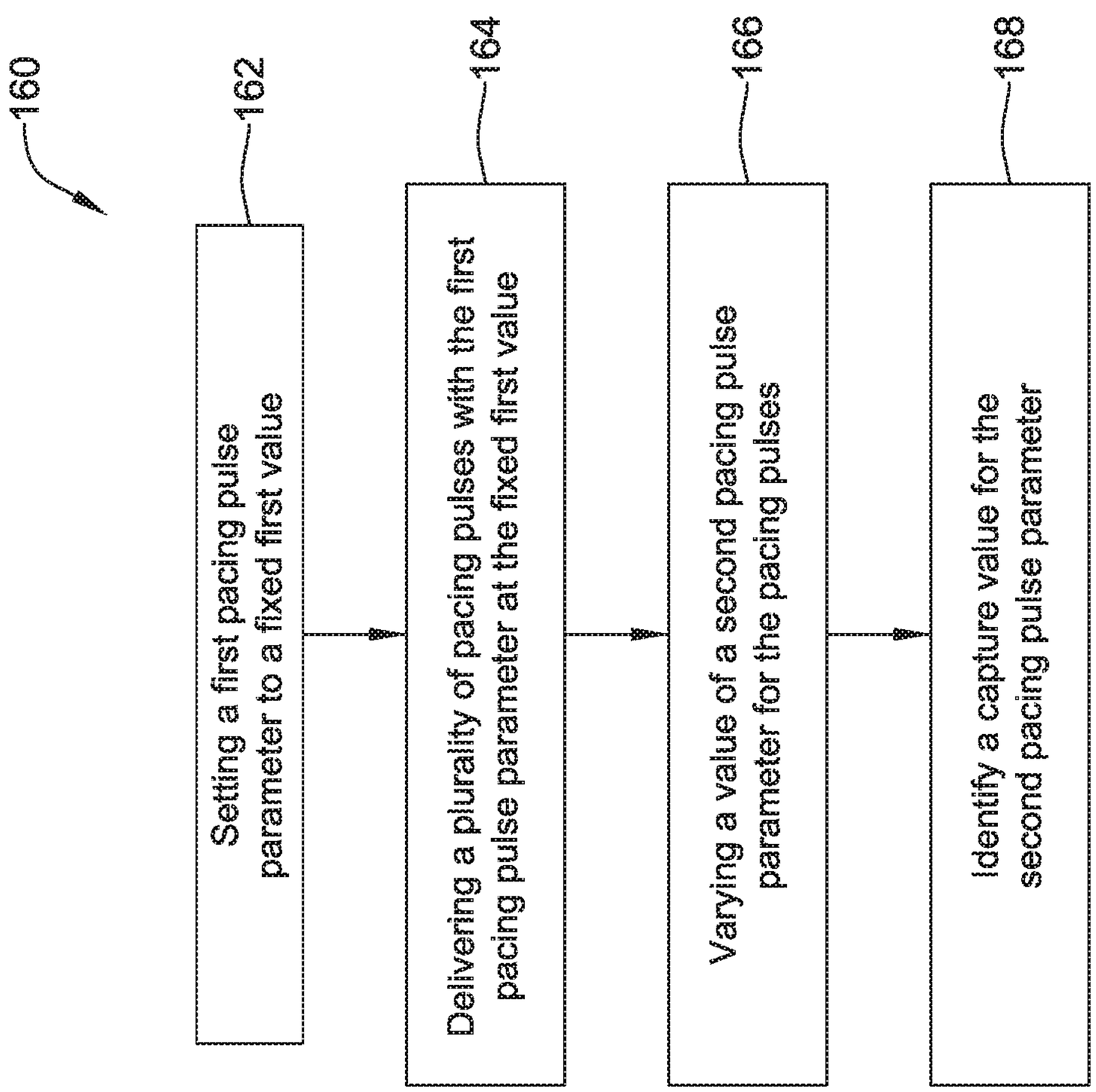
160
162
Setting a first pacing pulse parameter to a fixed first value
164
Delivering a plurality of pacing pulses with the first pacing pulse parameter at the fixed first value
166
Varying a value of a second pacing pulse parameter for the pacing pulses
168
Identify a capture value for the second pacing pulse parameter

FIG. 6

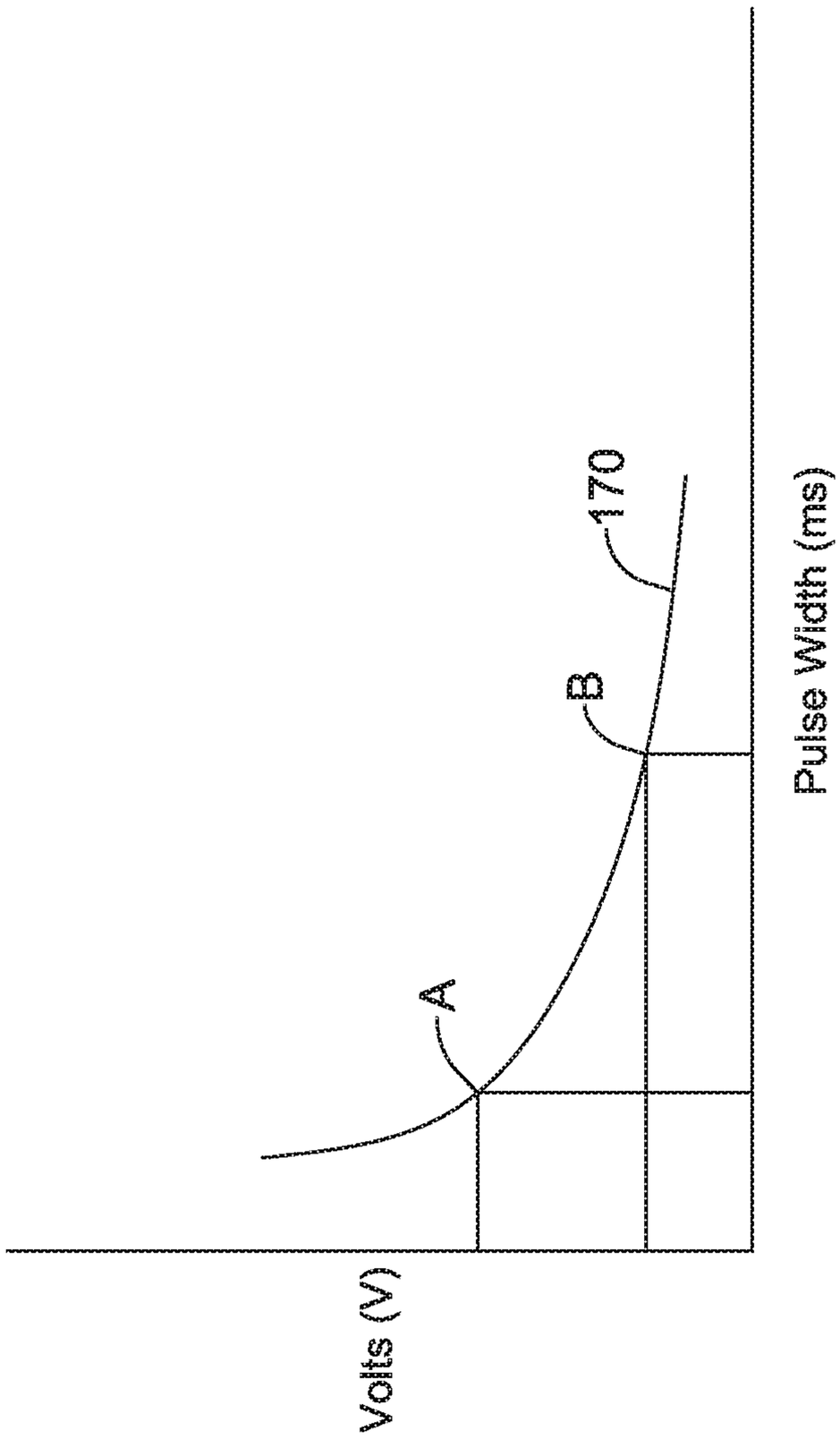

FIG. 7

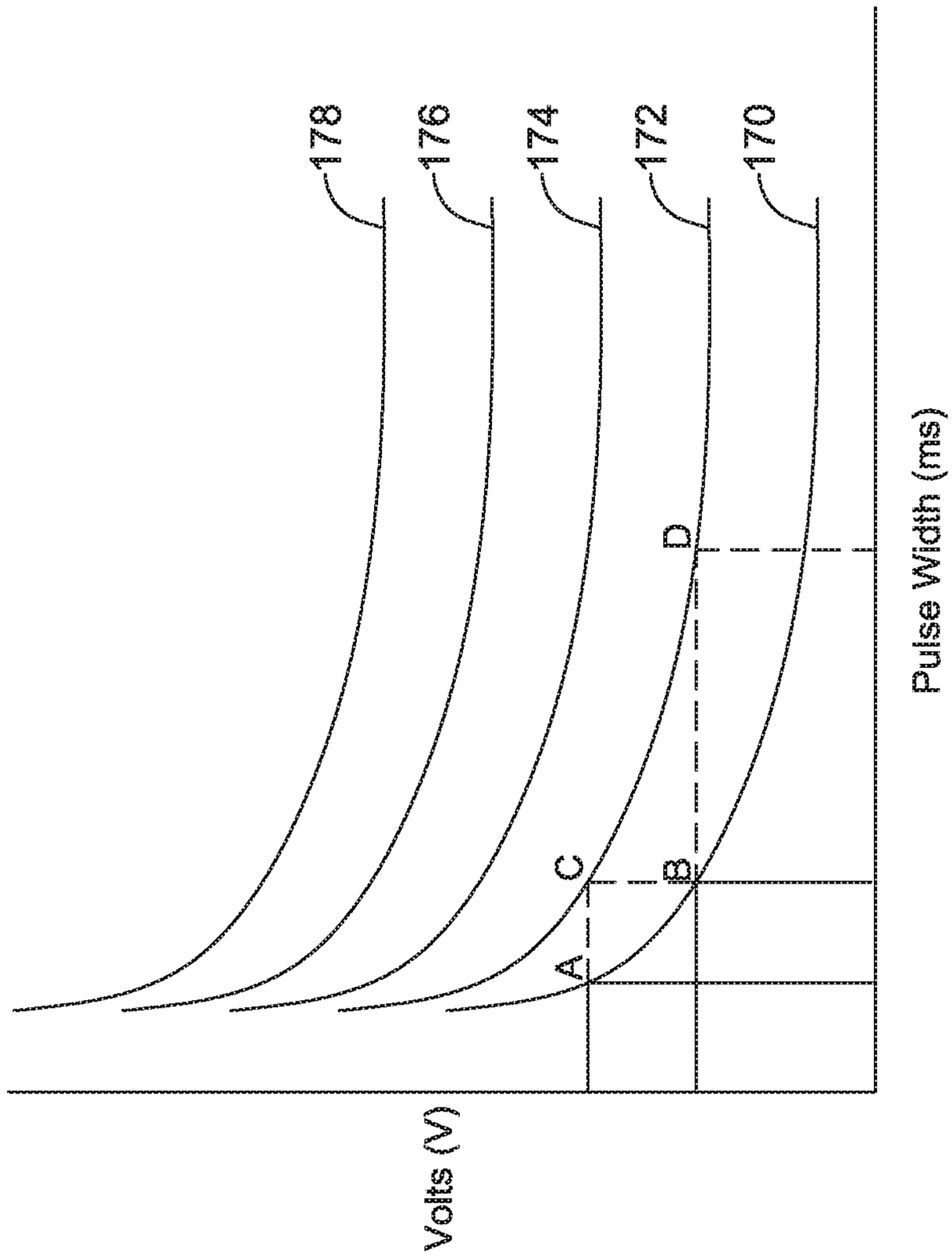

FIG. 8

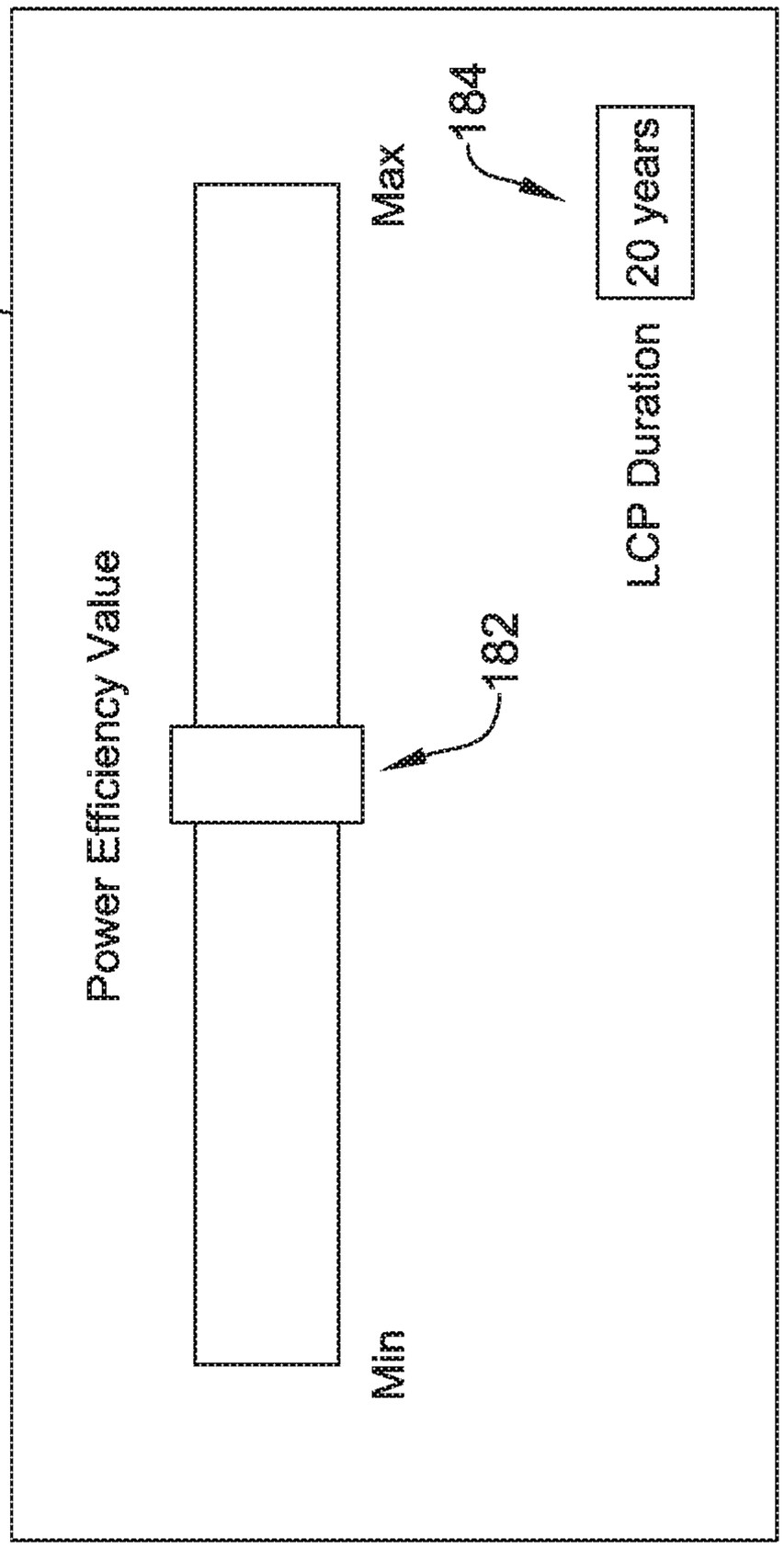
180
Power Efficiency Value
Max
Min
182
184
LCP Duration
20 years

FIG. 9

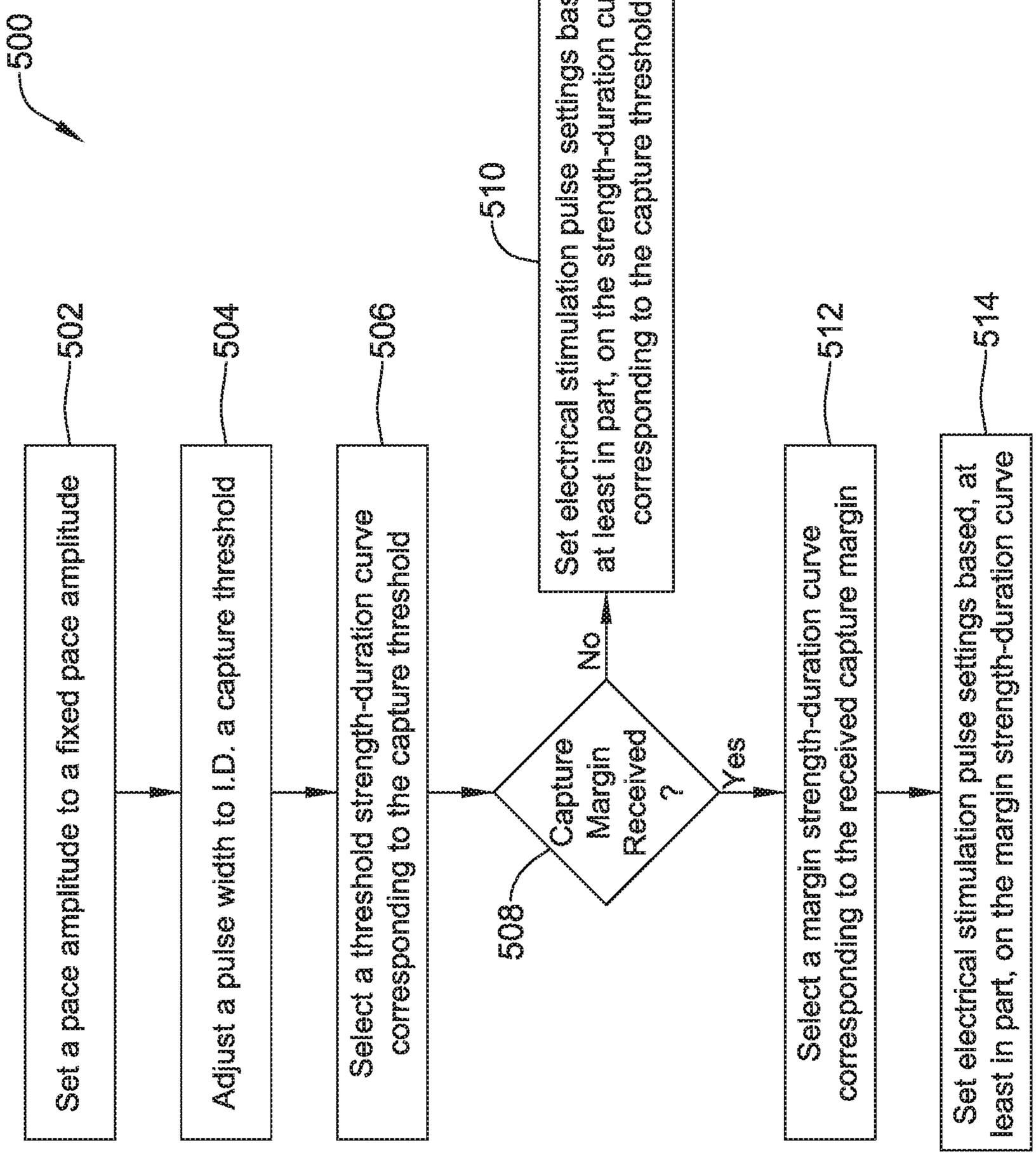
500
Set a pace amplitude to a fixed pace amplitude
502
Adjust a pulse width to I.D. a capture threshold
504
Select a threshold strength-duration curve corresponding to the capture threshold
506
508
Capture Margin Received ?
No
Yes
Set electrical stimulation pulse settings based, at least in part, on the strength-duration curve corresponding to the capture threshold
510
Select a margin strength-duration curve corresponding to the received capture margin
512
Set electrical stimulation pulse settings based, at least in part, on the margin strength-duration curve
514

FIG. 10

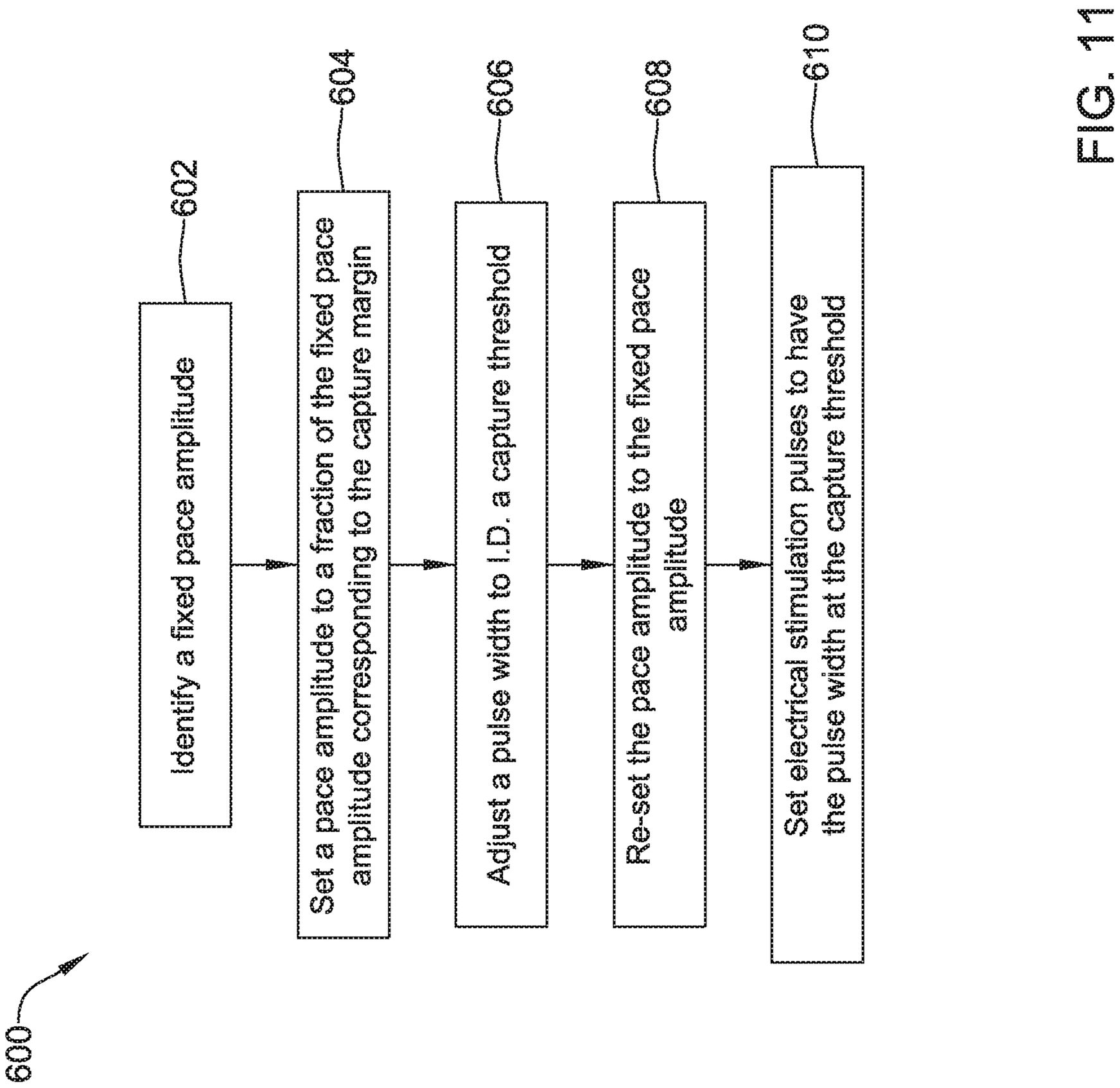
600
602
Identify a fixed pace amplitude
604
Set a pace amplitude to a fraction of the fixed pace amplitude corresponding to the capture margin
606
Adjust a pulse width to I.D. a capture threshold
608
Re-set the pace amplitude to the fixed pace amplitude
610
Set electrical stimulation pulses to have the pulse width at the capture threshold

FIG. 6

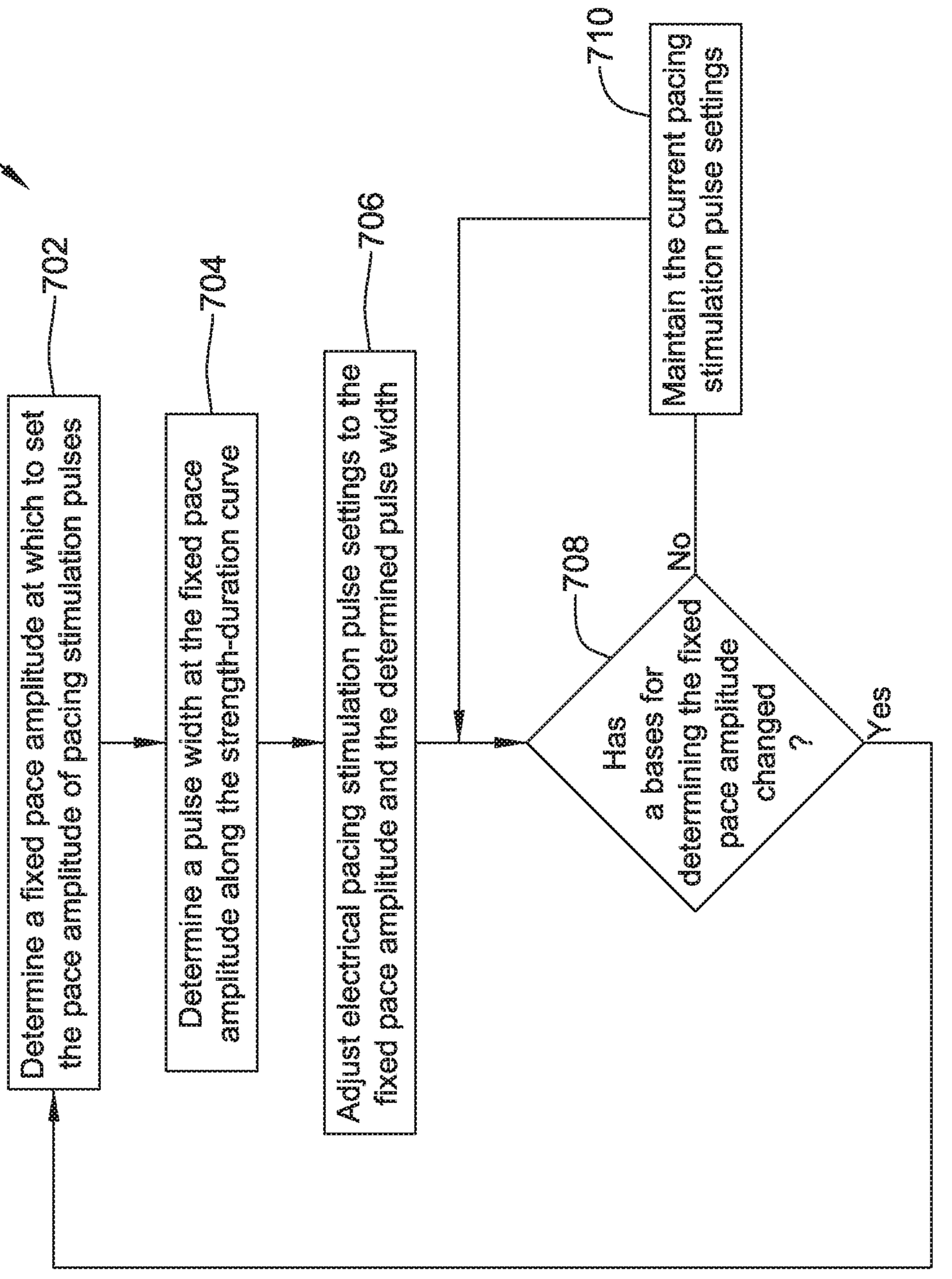
700
Determine a fixed pace amplitude at which to set the pace amplitude of pacing stimulation pulses
702
Determine a pulse width at the fixed pace amplitude along the strength-duration curve
704
Adjust electrical pacing stimulation pulse settings to the fixed pace amplitude and the determined pulse width
706
Has a bases for determining the fixed pace amplitude changed ?
708
No
Yes
Maintain the current pacing stimulation pulse settings
710

FIG. 12

SYSTEMS, DEVICES, AND METHODS FOR SETTING CARDIAC PACING PULSE PARAMETERS FOR A CARDIAC PACING DEVICE

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 62/419,731 filed on Nov. 9, 2016, the disclosure of which is incorporated herein by reference.

TECHNICAL FIELD

The present disclosure generally relates to cardiac pacing devices, and more particularly to systems, devices, and methods for setting pacing pulse parameters for such cardiac pacing devices.

BACKGROUND

Pacing instruments can be used to treat patients suffering from various heart conditions that result in a reduced ability of the heart to deliver sufficient amounts of blood to a patient's body. These heart conditions may lead to rapid, irregular, and/or inefficient heart contractions. To help alleviate some of these conditions, various devices (e.g., pacemakers, defibrillators, etc.) can be implanted in a patient's body. Such devices may monitor and provide electrical stimulation to the heart to help the heart operate in a more normal, efficient and/or safe manner. What would be desirable are improved systems, devices, and methods for setting pacing pulse parameters for such devices.

SUMMARY

The present disclosure generally relates to cardiac pacing devices, and more particularly to systems, devices, and methods for setting pacing pulse parameters for such cardiac pacing devices.

In an illustrative embodiment, the cardiac pacing device may include a leadless cardiac pacemaker (LCP). The leadless cardiac pacemaker may be configured to be implanted in or on a patient's heart and may deliver pacing pulses to the patient's heart. While a leadless cardiac pacemaker is used as an example in this disclosure, it is contemplated that the concepts disclosed herein may be applied to any suitable cardiac pacing device that is configured to delivery cardiac pacing pulses to a patient's heart.

An illustrative leadless cardiac pacemaker may comprise a power supply for providing a power supply voltage, a pair of electrodes for delivering pacing pulses to the heart of the patient, and a controller operably connected to the pair of electrodes and the power supply. The controller may identify a capture threshold and deliver, via the pair of electrodes, a plurality of pacing pulses each having a pace amplitude and a pacing pulse width. The controller may identify a capture threshold by setting the pace amplitude to the power supply voltage and then deliver, via the pair of electrodes, a plurality of pacing pulses having the pace amplitude with different pulse widths to identity the capture pulse width that corresponds to the capture threshold of the heart. Once the capture pulse width has been identified, the controller may deliver via the pair of electrodes a plurality of pacing pulses having the pace amplitude and a pacing pulse width that is greater than the capture pulse width by a pulse width margin.

By having the pace amplitude set to the power supply voltage (e.g. battery voltage), little or no power supply energy (e.g. battery energy) is wasted in converting the power supply voltage to the pace amplitude. In some cases, this can significantly increase the useful life expectancy of the leadless cardiac pacemaker.

Additionally, or alternatively to the first illustrative embodiment, the power supply may comprise a battery, and the power supply voltage may comprise a battery voltage provided by the battery.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the battery voltage, and thus the pace amplitude, may decay over time.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the controller may be configured to identify the capture threshold from time to time.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the controller may store data representing one or more strength-duration curves, and the controller may be configured to identify a capture threshold strength-duration curve based at least in part on the pace amplitude and the capture pulse width, and the controller may be further configured to identify the pulse width margin by referencing a different one of the strength-duration curves and the pace amplitude.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, wherein if the power supply voltage changes, and thus the pace amplitude changes, the controller may be configured to automatically adjust the pacing pulse width based at least in part on the different one of the strength-duration curves and the changed pace amplitude, without having to update the capture threshold by delivering via the pair of electrodes a plurality of pacing pulses having the changed pace amplitude and different pulse widths.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the controller may be configured to receive the data representing the one or more strength-duration curves from a remote device.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the controller may be further configured to receive a user selectable power efficiency value, and wherein the pulse width margin may be based, at least in part, on the user selectable power efficiency value.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the user selectable power efficiency value may be received from a remote device.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the remote device may comprise a user interface including a display, wherein a user may use the user interface to select the user selectable power efficiency value.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the user interface may display a slider that allows the user to select the user selectable power efficiency value from a range of allowable user selectable power efficiency values.

Additionally, or alternatively, in any of the above embodiments with respect to the first illustrative embodiment, the user interface may display a dynamic indicator of an expected life time of the leadless cardiac pacemaker based, at least in part, on the user selectable power efficiency value.

In second illustrative embodiment, a leadless cardiac pacemaker system for delivering pacing pulses to a heart of a patient may comprise a remote device and a leadless cardiac pacemaker that is in communication with the remote device. The remote device may have a user interface with a display for receiving a selection of a user selectable power efficiency value. The leadless cardiac pacemaker may comprise a power supply for providing a power supply voltage, a pair of electrodes for delivering pacing pulses to the heart of the patient, and a controller operably connected to the pair of electrodes and the power supply. The controller identify a pulse width and pulse amplitude combination that corresponds to a capture threshold. The controller may also receive the user selectable power efficiency value from the remote device, and may apply a capture margin to one or more of the pulse width and pulse amplitude that correspond to the capture threshold, resulting in a pacing pulse width and a pacing pulse amplitude. The capture margin may be based at least in part on the user selectable power efficiency value. The controller may then deliver pacing pulses to the heart using the pacing pulse width and the pacing pulse amplitude.

Additionally, or alternatively, the second illustrative embodiment may further comprise the controller being configured to store data representing one or more strength-duration curves, and wherein the controller may be configured to identify the capture margin by indexing the user selectable power efficiency value into the data representing one or more strength-duration curves.

Additionally, or alternatively, to any of the above embodiments with respect to the second illustrative embodiment, wherein the remote device displays on the display a slider that allows the user to select the user selectable power efficiency value from a range of allowable user selectable power efficiency values, and a dynamic indicator of an expected life time of the leadless cardiac pacemaker based, at least in part, on the user selectable power efficiency value.

In a third illustrative embodiment, a leadless cardiac pacemaker (LCP) for delivering pacing pulses to a heart of a patient may comprise a pair of electrodes for delivering pacing pulses to the heart of the patient and a controller operably connected to the pair of electrodes. The controller may identify a capture threshold by delivering via the pair of electrodes a plurality of pacing pulses while varying a first pacing pulse parameter value while leaving a second pacing pulse parameter value fixed in order to identity a capture value for the first pacing pulse parameter. Further, the controller may deliver via the pair of electrodes a plurality of pacing pulses that each have the first pacing pulse parameter value at the capture value and the second pacing pulse parameter value at a capture margin above the fixed second pacing pulse parameter value.

Additionally, or alternatively, the third illustrative embodiment may further comprise wherein the first pacing pulse parameter is pulse width and the second pacing pulse parameter is pulse amplitude.

Additionally, or alternatively, to any of the above embodiments with respect to the third illustrative embodiment, the leadless cardiac pacemaker may further comprise a battery that provides a battery voltage, and wherein the fixed second pacing pulse parameter value may be a predetermined fraction of the battery voltage.

Additionally, or alternatively, to any of the above embodiments with respect to the third illustrative embodiment, the second pacing pulse parameter value at the capture margin above the fixed second pacing pulse parameter value may correspond to the battery voltage.

Additionally, or alternatively, to any of the above embodiments with respect to the third illustrative embodiment, the first pacing pulse parameter may be pulse amplitude and the second pacing pulse parameter may be pulse width.

Additionally, or alternatively, to any of the above embodiments with respect to the third illustrative embodiment, the controller may store data representing one or more strength-duration curves, and the controller may be configured to identify the capture margin based at least in part on one or more of the strength-duration curves.

In a fourth illustrative embodiment, a leadless cardiac pacemaker (LCP) for delivering pacing pulses to a heart of a patient may comprise a pair of electrodes for delivering pacing pulses to the heart of the patient and a controller operably connected to the pair of electrodes. The controller identify a pulse width and pulse amplitude combination that corresponds to a capture threshold. The controller may also receive a user selectable power efficiency value from a remote device. The controller may apply a capture margin to one or more of the pulse width and pulse amplitude that correspond to the capture threshold, resulting in a pacing pulse width and a pacing pulse amplitude. The capture margin may be based, at least in part, on the user selectable power efficiency value. The controller may then deliver pacing pulses using the pacing pulse width and the pacing pulse amplitude.

Additionally, or alternatively, the fourth illustrative embodiment may further comprise the controller being configured to store data representing one or more strength-duration curves, and wherein the controller may be configured to identify the capture margin by indexing the user selectable power efficiency value into the data representing one or more strength-duration curves.

Additionally, or alternatively, to any of the above embodiments with respect to the fourth illustrative embodiment, the controller may be configured to receive the data representing one or more strength-duration curves from the remote device.

Additionally, or alternatively, to any of the above embodiments with respect to the fourth illustrative embodiment, the remote device may comprise a user interface including a display, wherein a user may use the user interface to select the user selectable power efficiency value.

Additionally, or alternatively, to any of the above embodiments with respect to the fourth illustrative embodiment, the remote device may display a slider on the display that allows the user select the user selectable power efficiency value from a range of allowable user selectable power efficiency values.

Additionally, or alternatively, to any of the above embodiments with respect to the fourth illustrative embodiment, the remote device may display a dynamic indicator of an expected life time of the leadless cardiac pacemaker based, at least in part, on the user selectable power efficiency value.

Additionally, or alternatively, to any of the above embodiments with respect to the fourth illustrative embodiment, the leadless cardiac pacemaker may further comprise a battery for providing a battery voltage, and wherein the pacing pulse amplitude is set to the battery voltage.

The above summary is not intended to describe each embodiment or every implementation of the present disclosure. Advantages and attainments, together with a more complete understanding of the disclosure, will become apparent and appreciated by referring to the following description and claims taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosure may be more completely understood in consideration of the following description of various illustrative embodiments in connection with the accompanying drawings, in which:

FIG. **1** is a schematic block diagram of an illustrative leadless cardiac pacemaker (LCP);

FIG. **2** is a schematic block diagram of another illustrative medical device;

FIG. **3** is a schematic diagram of an exemplary medical system that includes multiple LCPs and/or other devices in communication with one another;

FIG. **4** is a schematic diagram of a system including an LCP and another medical device, in accordance with another embodiment of the present disclosure;

FIG. **5** depicts a schematic flow diagram of an illustrative method for providing pacing stimulation pulses from an LCP;

FIG. **6** depicts a schematic flow diagram of an illustrative method for identifying a capture threshold with an LCP;

FIG. **7** depicts a graph of an illustrative strength-duration curve;

FIG. **8** depicts a graph of a plurality of illustrative strength-duration curves;

FIG. **9** depicts a schematic diagram of an illustrative user interface of a remote device used in conjunction with an LCP;

FIG. **10** depicts a schematic flow diagram of an illustrative method for setting parameters of a pacing stimulation pulse provided by an LCP;

FIG. **11** depicts a schematic flow diagram of another illustrative method for setting parameters of a pacing stimulation pulse provided by an LCP; and

FIG. **12** depicts a schematic flow diagram of an illustrative method for adjusting, over time, parameters of a pacing stimulation pulse provide by an LCP.

While the disclosure is amenable to various modifications and alternative forms, specifics thereof have been shown by way of embodiment in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit aspects of the disclosure to the particular illustrative embodiments described. On the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the disclosure.

DESCRIPTION

The following description should be read with reference to the drawings in which similar elements in different drawings are numbered the same. The description and the drawings, which are not necessarily to scale, depict illustrative embodiments and are not intended to limit the scope of the disclosure.

The present disclosure generally relates to cardiac pacing devices, and more particularly to systems, devices, and methods for setting pacing pulse parameters for such cardiac pacing devices. In an illustrative embodiment, the cardiac pacing device may include a leadless cardiac pacemaker (LCP). The leadless cardiac pacemaker may be configured to be implanted in or on a patient's heart and may deliver pacing pulses to the patient's heart. While a leadless cardiac pacemaker is used as an example in this disclosure, it is contemplated that the concepts disclosed herein may be applied to any suitable cardiac pacing device that is configured to delivery cardiac pacing pulses to a patient's heart.

FIG. **1** is a schematic block diagram of an illustrative leadless cardiac pacemaker (LCP). The illustrative LCP may be implanted on the heart or within a chamber of the heart and may operate to sense physiological signals and parameters and deliver one or more types of electrical stimulation therapy to the heart of the patient. Example electrical stimulation therapy may include bradycardia pacing, rate responsive pacing therapy, cardiac resynchronization therapy (CRT), anti-tachycardia pacing (ATP) therapy and/or the like. The disclosed concepts may be implemented in other IMDs and/or other devices including, but not limited to, pacemakers with leads, defibrillators, and/or other implantable or non-implantable devices.

As can be seen in FIG. **1**, LCP **100** may be a compact device with all components housed within LCP **100** or directly on housing **120**. In some instances, LCP **100** may include communication module **102**, pulse generator module **104**, electrical sensing module **106** (e.g., including one or more electrical sensors), mechanical sensing module **108** (e.g., including one or more mechanical sensors), processing module **110** (e.g., a controller including memory and one or more processors), energy storage module **112**, and electrodes **114**, **114'**. Via circuitry, the electrodes **114**, **114'** may be part of and/or may be in communication with (e.g., operatively coupled to) the communication module **102**, the pulse generator module **104**, electrical sensing module **106**, the mechanical sensing module **108**, the processing module **110**, and/or the energy storage module **112**.

As depicted in FIG. **1**, LCP **100** may include electrodes **114**, which can be secured relative to housing **120** and electrically exposed to tissue and/or blood surrounding LCP **100**. Electrodes **114** may generally conduct electrical signals to and/or from LCP **100** and the surrounding tissue and/or blood. Such electrical signals may include communication signals, electrical stimulation pulses, and intrinsic cardiac electrical signals, to name a few. Intrinsic cardiac electrical signals may include electrical signals generated by the heart and may be represented by an electrocardiogram (ECG). The electrodes may be considered a sensor capable of sensing each of a plurality of heart beats.

Electrodes **114** may include one or more biocompatible conductive materials such as various metals or alloys that are known to be safe for implantation within a human body. In some instances, electrodes **114** may be generally disposed on either end of LCP **100** and may be in electrical communication with one or more of modules **102**, **104**, **106**, **108**, and **110**. In embodiments where electrodes **114** (e.g., two or more electrodes **114**) are secured directly to housing **120**, an insulative material may electrically isolate the electrodes **114** from adjacent electrodes, housing **120**, and/or other parts of LCP **100**. In some instances, some or all of electrodes **114** may be spaced from housing **120** and connected to housing **120** and/or other components of LCP **100** through connecting wires. In such instances, the electrodes **114** may be placed on a tail (not shown) that extends out away from the housing **120**.

As shown in FIG. **1**, in some embodiments, LCP **100** may include electrodes **114'**. Electrodes **114'** may be in addition to electrodes **114**, or may replace one or more of electrodes **114**. Electrodes **114'** may be similar to electrodes **114** except that electrodes **114'** are disposed on the sides of LCP **100**. In some cases, electrodes **114'** may increase the number of electrodes by which LCP **100** may deliver communication signals and/or electrical stimulation pulses, and/or may sense intrinsic cardiac electrical signals, communication signals, and/or electrical stimulation pulses.

Electrodes **114** and/or **114'** may assume any of a variety of sizes and/or shapes, and may be spaced at any of a variety of spacings. For example, electrodes **114** may have an outer diameter of two to twenty millimeters (mm). In other embodiments, electrodes **114** and/or **114'** may have a diameter of two, three, five, seven millimeters (mm), or any other suitable diameter, dimension and/or shape. Example lengths for electrodes **114** and/or **114'** may include, for example, one, three, five, ten millimeters (mm), or any other suitable length. As used herein, the length is a dimension of electrodes **114** and/or **114'** that extends away from the outer surface of the housing **120**. In some instances, at least some of electrodes **114** and/or **114'** may be spaced from one another by a distance of twenty, thirty, forty, fifty millimeters (mm), or any other suitable spacing. The electrodes **114** and/or **114'** of a single device may have different sizes with respect to each other, and the spacing and/or lengths of the electrodes on the device may or may not be uniform.

In the embodiment shown, communication module **102** may be electrically coupled to electrodes **114** and/or **114'** and may be configured to deliver communication pulses to tissues of the patient for communicating with other devices such as sensors, programmers, other medical devices, and/or the like. Communication signals, as used herein, may be any modulated signal that conveys information to another device, either by itself or in conjunction with one or more other modulated signals. In some embodiments, communication signals may be limited to sub-threshold signals that do not result in capture of the heart yet still convey information. The communication signals may be delivered to another device that is located either external or internal to the patient's body. In some instances, the communication may take the form of distinct communication pulses separated by various amounts of time. In some of these cases, the timing between successive pulses may convey information. Communication module **102** may additionally be configured to sense for communication signals delivered by other devices, which may be located external or internal to the patient's body.

Communication module **102** may communicate to help accomplish one or more desired functions. Some example functions include delivering sensed data, using communicated data for determining occurrences of events such as arrhythmias, coordinating delivery of electrical stimulation therapy, and/or other functions. In some cases, LCP **100** may use communication signals to communicate raw information, processed information, messages and/or commands, and/or other data. Raw information may include information such as sensed electrical signals (e.g. a sensed ECG), signals gathered from coupled sensors, and the like. In some embodiments, the processed information may include signals that have been filtered using one or more signal processing techniques. Processed information may also include parameters and/or events that are determined by the LCP **100** and/or another device, such as a determined heart rate, timing of determined heartbeats, timing of other determined events, determinations of threshold crossings, expirations of monitored time periods, accelerometer signals, activity level parameters, blood-oxygen parameters, blood pressure parameters, heart sound parameters, and the like. Messages and/or commands may include instructions or the like directing another device to take action, notifications of imminent actions of the sending device, requests for reading from the receiving device, requests for writing data to the receiving device, information messages, and/or other messages commands.

In at least some embodiments, communication module **102** (or LCP **100**) may further include switching circuitry to selectively connect one or more of electrodes **114** and/or **114'** to communication module **102** in order to select which electrodes **114** and/or **114'** that communication module **102** delivers communication pulses. It is contemplated that communication module **102** may be communicating with other devices via conducted signals, radio frequency (RF) signals, optical signals, acoustic signals, inductive coupling, and/or any other suitable communication methodology.

Where communication module **102** generates electrical communication signals, communication module **102** may include one or more capacitor elements and/or other charge storage devices to aid in generating and delivering communication signals. In the embodiment shown, communication module **102** may use energy stored in energy storage module **112** to generate the communication signals. In at least some examples, communication module **102** may include a switching circuit that is connected to energy storage module **112** and, with the switching circuitry, may connect energy storage module **112** to one or more of electrodes **114/114'** to generate the communication signals.

As shown in FIG. **1**, a pulse generator module **104** may be electrically connected to one or more of electrodes **114** and/or **114'**. Pulse generator module **104** may be configured to generate electrical stimulation pulses and deliver the electrical stimulation pulses to tissues of a patient via one or more of the electrodes **114** and/or **114'** in order to effectuate one or more electrical stimulation therapies. Each electrical stimulation pulse may have a pulse amplitude and a pulse width.

Electrical stimulation pulses as used herein are meant to encompass any electrical signals that may be delivered to tissue of a patient for purposes of treatment of any type of disease or abnormality. For example, when used to treat heart disease, the pulse generator module **104** may generate electrical stimulation pacing pulses for capturing the heart of the patient, i.e. causing the heart to contract in response to the delivered electrical stimulation pulse. In some of these cases, LCP **100** may vary the rate at which pulse generator module **104** generates the electrical stimulation pulses, for example in rate adaptive pacing. In other embodiments, the electrical stimulation pulses may include defibrillation/cardioversion pulses for shocking the heart out of fibrillation or into a normal heart rhythm. In yet other embodiments, the electrical stimulation pulses may include anti-tachycardia pacing (ATP) pulses. It should be understood that these are just some examples. When used to treat other ailments, the pulse generator module **104** may generate electrical stimulation pulses suitable for neurostimulation therapy or the like.

Pulse generator module **104** may include one or more capacitor elements and/or other charge storage devices to aid in generating and delivering appropriate electrical stimulation pulses. In at least some embodiments, pulse generator module **104** may use energy stored in energy storage module **112** to generate the electrical stimulation pulses. In some particular embodiments, pulse generator module **104** may include a switching circuit that is connected to energy storage module **112** and may connect energy storage module **112** to one or more of electrodes **114/114'** to generate electrical stimulation pulses.

LCP **100** may include an electrical sensing module **106**. Electrical sensing module **106** may be configured to sense intrinsic cardiac electrical signals conducted from electrodes **114** and/or **114'** to electrical sensing module **106**. For example, electrical sensing module **106** may be electrically

connected to one or more electrodes **114** and/or **114'** and electrical sensing module **106** may be configured to receive cardiac electrical signals conducted through electrodes **114** and/or **114'** via a sensor amplifier or the like. In some embodiments, the cardiac electrical signals may represent local information from the chamber in which LCP **100** is implanted. For instance, if LCP **100** is implanted within a ventricle of the heart, cardiac electrical signals sensed by LCP **100** through electrodes **114** and/or **114'** may represent ventricular cardiac electrical signals. The electrical sensing module **106** may, in some cases, be configured to identify each of a plurality of heart beats as an intrinsically initiated heart beat or a pace initiated heart beat.

Further, LCP **100** may include a mechanical sensing module **108**. Mechanical sensing module **108** may include, or be electrically connected to, various sensors, such as accelerometers, including multi-axis accelerometers such as two- or three-axis accelerometers, gyroscopes, including multi-axis gyroscopes such as two- or three-axis gyroscopes, blood pressure sensors, heart sound sensors, piezoelectric sensors, blood-oxygen sensors, and/or other sensors which measure one or more physiological parameters of the heart and/or patient. Mechanical sensing module **108**, when present, may gather signals from the sensors indicative of the various physiological parameters.

Both electrical sensing module **106** and mechanical sensing module **108** may be connected to processing module **110** and may provide signals representative of the sensed cardiac electrical signals and/or physiological signals to processing module **110**. Although described with respect to FIG. **1** as separate sensing modules, in some embodiments, electrical sensing module **106** and mechanical sensing module **108** may be combined into a single module. In at least some examples, LCP **100** may only include one of electrical sensing module **106** and mechanical sensing module **108**. In some cases, any combination of the processing module **110**, electrical sensing module **106**, mechanical sensing module **108**, communication module **102**, pulse generator module **104** and/or energy storage module may be considered a controller of the LCP **100**.

Processing module **110** (e.g., a controller) may be configured to direct the operation of LCP **100** and may, in some embodiments, be termed a controller. For example, processing module **110** may be configured to receive cardiac electrical signals from electrical sensing module **106** and/or physiological signals from mechanical sensing module **108**. Based on the received signals, processing module **110** may, for example, adjust the rate of pacing based on the activity level of the patient (e.g. rate adaptive pacing). When so provided, processing module **110** may monitor one or more physiological parameters of the patient which may indicate a need for an increased heart rate (e.g. due to increased metabolic demand) and increase the rate at which pulse generator module **104** generates electrical stimulation pulses. Determining an activity level of the patient using a motion sensor (e.g. accelerometer) of the mechanical sensing module **108** of the LCP **100** can be challenging because the motion detected by the motion sensor not only includes the activity level of the patient but also the motion of the beating heart. FIGS. **6-10** describes illustrative methods for aiding in rate responsive pacing using a motion sensor (e.g. accelerometer) in an LCP.

In some cases, the processing module **110** may determine occurrences and types of arrhythmias and other determinations such as whether LCP **100** has become dislodged. Processing module **110** may further receive information from communication module **102**. In some embodiments, processing module **110** may additionally use such received information to determine occurrences and types of arrhythmias and/or and other determinations such as whether LCP **100** has become dislodged. In still some additional embodiments, LCP **100** may use the received information instead of the signals received from electrical sensing module **106** and/or mechanical sensing module **108**—for instance if the received information is deemed to be more accurate than the signals received from electrical sensing module **106** and/or mechanical sensing module **108** or if electrical sensing module **106** and/or mechanical sensing module **108** have been disabled or omitted from LCP **100**.

After determining an occurrence of an arrhythmia, processing module **110** may control pulse generator module **104** to generate electrical stimulation pulses in accordance with one or more electrical stimulation therapies to treat the determined arrhythmia. For example, processing module **110** may control pulse generator module **104** to generate pacing pulses with varying and/or fixed parameters (e.g., one or more of a pulse width, a pulse amplitude and/or other parameters) and in different sequences to effectuate one or more electrical stimulation therapies. As one example, in controlling pulse generator module **104** to deliver bradycardia pacing therapy, processing module **110** may control pulse generator module **104** to deliver pacing pulses having a particular pulse width and pulse amplitude designed to capture the heart of the patient at a regular interval to help prevent a metric of the heart of a patient from falling below a predetermined threshold.

For ATP therapy, processing module **110** may control pulse generator module **104** to deliver pacing pulses at a rate faster than an intrinsic heart rate of a patient in an attempt to force the heart to beat in response to the delivered pacing pulses rather than in response to intrinsic cardiac electrical signals. Once the heart is following the pacing pulses, processing module **110** may control pulse generator module **104** to reduce the rate of delivered pacing pulses down to a safer level. In Cardiac Resynchronization Therapy (CRT), processing module **110** may control pulse generator module **104** to deliver pacing pulses in coordination with another device to cause the heart to contract more efficiently. In cases where pulse generator module **104** is capable of generating defibrillation and/or cardioversion pulses for defibrillation/cardioversion therapy, processing module **110** may control pulse generator module **104** to generate such defibrillation and/or cardioversion pulses. In some cases, processing module **110** may control pulse generator module **104** to generate electrical stimulation pulses to provide electrical stimulation therapies different than those examples described above.

Aside from controlling pulse generator module **104** to generate different types of electrical stimulation pulses and in different sequences, in some embodiments, processing module **110** may also control pulse generator module **104** to generate the various electrical stimulation pulses with varying pulse parameters. For example, each electrical stimulation pulse may have a pulse width and a pulse amplitude. Processing module **110** may control pulse generator module **104** to generate the various electrical stimulation pulses with specific pulse widths and pulse amplitudes. For example, processing module **110** may cause pulse generator module **104** to adjust the pulse width and/or the pulse amplitude of electrical stimulation pulses if the electrical stimulation pulses are not effectively capturing the heart. Such control of the specific parameters of the various electrical stimulation pulses may help LCP **100** provide more effective delivery of electrical stimulation therapy.

In some embodiments, processing module **110** may further control communication module **102** to send information to other devices. For example, processing module **110** may control communication module **102** to generate one or more communication signals for communicating with other devices of a system of devices. For instance, processing module **110** may control communication module **102** to generate communication signals in particular pulse sequences, where the specific sequences convey different information. Communication module **102** may also receive communication signals for potential action by processing module **110**.

In further embodiments, processing module **110** may control switching circuitry by which communication module **102** and pulse generator module **104** deliver communication signals and/or electrical stimulation pulses to tissue of the patient. As described above, both communication module **102** and pulse generator module **104** may include circuitry for connecting one or more electrodes **114** and/**114'** to communication module **102** and/or pulse generator module **104** so those modules may deliver the communication signals and electrical stimulation pulses to tissue of the patient. The specific combination of one or more electrodes by which communication module **102** and/or pulse generator module **104** deliver communication signals and electrical stimulation pulses may influence the reception of communication signals and/or the effectiveness of electrical stimulation pulses. Although it was described that each of communication module **102** and pulse generator module **104** may include switching circuitry, in some embodiments, LCP **100** may have a single switching module connected to the communication module **102**, the pulse generator module **104**, and electrodes **114** and/or **114'**. In such embodiments, processing module **110** may control the switching module to connect modules **102**/**104** and electrodes **114**/**114'** as appropriate.

In some embodiments, processing module **110** may include a pre-programmed chip, such as a very-large-scale integration (VLSI) chip or an application specific integrated circuit (ASIC). In such embodiments, the chip may be pre-programmed with control logic in order to control the operation of LCP **100**. By using a pre-programmed chip, processing module **110** may use less power than other programmable circuits while able to maintain basic functionality, thereby potentially increasing the battery life of LCP **100**. In other instances, processing module **110** may include a programmable microprocessor or the like. Such a programmable microprocessor may allow a user to adjust the control logic of LCP **100** after manufacture, thereby allowing for greater flexibility of LCP **100** than when using a pre-programmed chip. In still other embodiments, processing module **110** may not be a single component. For example, processing module **110** may include multiple components positioned at disparate locations within LCP **100** in order to perform the various described functions. For example, certain functions may be performed in one component of processing module **110**, while other functions are performed in a separate component of processing module **110**.

Processing module **110** may include a memory circuit and processing module **110** may store information on and read information from the memory circuit. In other embodiments, LCP **100** may include a separate memory circuit (not shown) that is in communication with processing module **110**, such that processing module **110** may read and write information to and from the separate memory circuit. The memory circuit, whether part of processing module **110** or separate from processing module **110**, may be volatile memory, non-volatile memory, or a combination of volatile memory and non-volatile memory.

Energy storage module **112** may be a power supply and provide a power source (e.g., a power supply voltage) to LCP **100** for its operations. In some embodiments, energy storage module **112** may be a non-rechargeable lithium-based battery. In other embodiments, the non-rechargeable battery may be made from other suitable materials. In some embodiments, energy storage module **112** may include a rechargeable battery. In still other embodiments, energy storage module **112** may include other types of energy storage devices such as capacitors or super capacitors.

To implant LCP **100** inside a patient's body, an operator (e.g., a physician, clinician, etc.), may fix LCP **100** to the cardiac tissue of the patient's heart. To facilitate fixation, LCP **100** may include one or more anchors **116**. The one or more anchors **116** are shown schematically in FIG. **1**. The one or more anchors **116** may include any number of fixation or anchoring mechanisms. For example, one or more anchors **116** may include one or more pins, staples, threads, screws, helix, tines, and/or the like. In some embodiments, although not shown, one or more anchors **116** may include threads on its external surface that may run along at least a partial length of an anchor member. The threads may provide friction between the cardiac tissue and the anchor to help fix the anchor member within the cardiac tissue. In some cases, the one or more anchors **116** may include an anchor member that has a cork-screw shape that can be screwed into the cardiac tissue. In other embodiments, anchor **116** may include other structures such as barbs, spikes, or the like to facilitate engagement with the surrounding cardiac tissue.

In some examples, LCP **100** may be configured to be implanted on a patient's heart or within a chamber of the patient's heart. For instance, LCP **100** may be implanted within any of a left atrium, right atrium, left ventricle, or right ventricle of a patient's heart. By being implanted within a specific chamber, LCP **100** may be able to sense cardiac electrical signals originating or emanating from the specific chamber that other devices may not be able to sense with such resolution. Where LCP **100** is configured to be implanted on a patient's heart, LCP **100** may be configured to be implanted on or adjacent to one of the chambers of the heart, or on or adjacent to a path along which intrinsically generated cardiac electrical signals generally follow. In these examples, LCP **100** may also have an enhanced ability to sense localized intrinsic cardiac electrical signals and deliver localized electrical stimulation therapy. In embodiments where LCP **100** includes an accelerometer, LCP **100** may additionally be able to sense the motion of the cardiac wall to which LCP **100** is attached.

FIG. **2** depicts an embodiment of another device, medical device (MD) **200**, which may operate to sense physiological signals and parameters and deliver one or more types of electrical stimulation therapy to tissues of the patient. In the embodiment shown, MD **200** may include a communication module **202**, a pulse generator module **204**, an electrical sensing module **206**, a mechanical sensing module **208**, a processing module **210**, and an energy storage module **218**. Each of modules **202**, **204**, **206**, **208**, and **210** may be similar to and/or different than modules **102**, **104**, **106**, **108**, and **110** of LCP **100** in one or more manners. Additionally, energy storage module **218** may be similar to and/or different than energy storage module **112** of LCP **100** in one or more manners. However, in some embodiments, MD **200** may have a larger volume within housing **220** than a volume of

LCP **100**. In such embodiments, MD **200** may include a larger energy storage module **218** and/or a larger processing module **210** capable of handling more complex operations than processing module **110** of LCP **100**.

While MD **200** may be another leadless device such as shown in FIG. **1**, in some instances MD **200** may include leads, such as leads **212**. Leads **212** may include electrical wires that conduct electrical signals between electrodes **214** and one or more modules located within housing **220**. In some cases, leads **212** may be connected to and extend away from housing **220** of MD **200**. In some embodiments, leads **212** may be implanted on, within, or adjacent to a heart of a patient. Leads **212** may contain one or more electrodes **214** positioned at various locations on leads **212** and various distances from housing **220**. Some leads **212** may only include a single electrode **214**, while other leads **212** may include multiple electrodes **214**. Generally, electrodes **214** may be positioned on leads **212** such that when leads **212** are implanted within the patient, one or more of the electrodes **214** are positioned to perform a desired function. In some cases, the one or more of the electrodes **214** may be in contact with the patient's cardiac tissue. In other cases, the one or more of the electrodes **214** may be positioned subcutaneously but adjacent the patient's heart.

MD **200** may also include one or more electrodes **214** not disposed on a lead **212**. For example, one or more electrodes **214** may be connected directly to housing **220**.

The electrodes **214** may conduct intrinsically generated electrical cardiac signals to leads **212**. Leads **212** may, in turn, conduct the received electrical cardiac signals to one or more of the modules **202**, **204**, **206**, and **208** of MD **200**.

In some cases, MD **200** may generate electrical stimulation signals (e.g., having a signal width and a signal amplitude, such as a pulse width and a pulse amplitude), and leads **212** may conduct the generated electrical stimulation signals to electrodes **214**. Electrodes **214** may then conduct the electrical stimulation signals to the cardiac tissue of the patient (either directly or indirectly).

Leads **212**, in some embodiments, may additionally contain one or more sensors, such as accelerometers, blood pressure sensors, heart sound sensors, blood-oxygen sensors, and/or other sensors which are configured to measure one or more physiological parameters of the heart and/or patient. In such embodiments, mechanical sensing module **208** may be in electrical communication with leads **212** and may receive signals generated from such sensors.

While not required, in some embodiments MD **200** may be an implantable medical device. In such embodiments, housing **220** of MD **200** may be implanted in, for example, a transthoracic region of the patient. Housing **220** may generally include any of a number of known materials that are safe for implantation in a human body and may, when implanted, hermetically seal the various components of MD **200** from fluids and tissues of the patient's body. In such embodiments, leads **212** may be implanted at one or more various locations within the patient, such as within the heart of the patient, adjacent to the heart of the patient, adjacent to the spine of the patient, or any other desired location.

In some embodiments, MD **200** may be an implantable cardiac pacemaker (ICP). In these embodiments, MD **200** may have one or more leads, for example leads **212**, which are implanted on or within the patient's heart. The one or more leads **212** may include one or more electrodes **214** that are in contact with cardiac tissue and/or blood of the patient's heart. MD **200** may be configured to sense intrinsically generated cardiac electrical signals and determine, for example, one or more cardiac arrhythmias based on analysis of the sensed signals. MD **200** may be configured to deliver CRT, ATP therapy, bradycardia therapy, and/or other therapy types via leads **212** implanted within the heart. In some embodiments, MD **200** may additionally be configured to provide defibrillation/cardioversion therapy.

In some instances, MD **200** may be an implantable cardioverter-defibrillator (ICD). In such embodiments, MD **200** may include one or more leads implanted within a patient's heart. MD **200** may also be configured to sense electrical cardiac signals, determine occurrences of tachyarrhythmias based on the sensed electrical cardiac signals, and deliver defibrillation and/or cardioversion therapy in response to determining an occurrence of a tachyarrhythmia (for example by delivering defibrillation and/or cardioversion pulses to the heart of the patient). In other embodiments, MD **200** may be a subcutaneous implantable cardioverter-defibrillator (SICD). In embodiments where MD **200** is an SICD, one of leads **212** may be a subcutaneously implanted lead. In at least some embodiments where MD **200** is an SICD, MD **200** may include only a single lead which is implanted subcutaneously but outside of the chest cavity, however this is not required.

In some embodiments, MD **200** may not be an implantable medical device. Rather, MD **200** may be a device external to the patient's body, and electrodes **214** may be skin-electrodes that are placed on a patient's body. In such embodiments, MD **200** may be able to sense surface electrical signals (e.g. electrical cardiac signals that are generated by the heart or electrical signals generated by a device implanted within a patient's body and conducted through the body to the skin). MD **200** may further be configured to deliver various types of electrical stimulation therapy, including, for example, defibrillation therapy via skin-electrodes **214**.

FIG. **3** illustrates an embodiment of a medical device system and a communication pathway through which multiple medical devices **100***a*, **100***b*, **306**, and/or **310** of the medical device system may communicate. In the embodiment shown, medical device system **300** may include a first LCP **100***a* and a second LCP **100***b*, external medical device **306**, and other sensors/devices **310**.

External device **306** may be a device disposed external to a patient's body, as described previously with respect to MD **200**. In at least some examples, external device **306** may represent an external support device such as a device programmer, as will be described in more detail below.

Other sensors/devices **310** may be any of the devices described previously with respect to MD **200**, such as ICPs, ICDs, and SICDs. Other sensors/devices **310** may also include various diagnostic sensors that gather information about the patient, such as accelerometers, blood pressure sensors, or the like. In some cases, other sensors/devices **310** may include an external programmer device that may be used to program one or more devices of system **300**.

Various devices of system **300** may communicate via communication pathway **308**. For example, LCPs **100***a* and/or **100***b* may sense intrinsic cardiac electrical signals and may communicate such signals to one or more other devices **100***a*/**100***b*, **306**, and **310** of system **300** via communication pathway **308**. In one embodiment, one or more of devices **100***a*/**100***b* may receive such signals and, based on the received signals, determine an occurrence of an arrhythmia. In some cases, device or devices **100***a*/**100***b* may communicate such determinations to one or more other devices **306** and **310** of system **300**. In some cases, one or more of devices **100***a*/**100***b*, **306**, and **310** of system **300** may take action based on the communicated determination of an

arrhythmia, such as by delivering a suitable electrical stimulation to the heart of the patient. One or more of devices **100***a*/**100***b*, **306**, and **310** of system **300** may additionally communicate command or response messages via communication pathway **308**. The command messages may cause a receiving device to take a particular action whereas response messages may include requested information or a confirmation that a receiving device did, in fact, receive a communicated message or data.

It is contemplated that the various devices of system **300** may communicate via pathway **308** using RF signals, inductive coupling, optical signals, acoustic signals, or any other signals suitable for communication. Additionally, in at least some embodiments, the various devices of system **300** may communicate via pathway **308** using multiple signal types. For instance, other sensors/device **310** may communicate with external device **306** using a first signal type (e.g. RF communication) but communicate with LCPs **100***a*/**100***b* using a second signal type (e.g. conducted communication). Further, in some embodiments, communication between devices may be limited. For instance, as described above, in some embodiments, LCPs **100***a*/**100***b* may communicate with external device **306** only through other sensors/devices **310**, where LCPs **100***a*/**100***b* may send signals to other sensors/devices **310**, and other sensors/devices **310** relay the received signals to external device **306**.

In some cases, the various devices of system **300** may communicate via pathway **308** using conducted communication signals. Accordingly, devices of system **300** may have components that allow for such conducted communication. For instance, the devices of system **300** may be configured to transmit conducted communication signals (e.g. a voltage and/or current waveform punctuated with current and/or voltage pulses, referred herein as electrical communication pulses) into the patient's body via one or more electrodes of a transmitting device, and may receive the conducted communication signals via one or more electrodes of a receiving device. The patient's body may "conduct" the conducted communication signals from the one or more electrodes of the transmitting device to the electrodes of the receiving device in the system **300**. In such embodiments, the delivered conducted communication signals may differ from pacing pulses, defibrillation and/or cardioversion pulses, or other electrical stimulation therapy signals. For example, the devices of system **300** may deliver electrical communication pulses at an amplitude/pulse width that is sub-threshold. That is, the communication pulses have an amplitude/pulse width designed to not capture the heart. In some cases, the amplitude/pulse width of the delivered electrical communication pulses may be above the capture threshold of the heart, but may be delivered during a refractory period of the heart and/or may be incorporated in or modulated onto a pacing pulse, if desired.

Additionally, unlike normal electrical stimulation therapy pulses, the electrical communication pulses may be delivered in specific sequences which convey information to receiving devices. For instance, delivered electrical communication pulses may be modulated in any suitable manner to encode communicated information. In some cases, the communication pulses may be pulse width modulated and/or amplitude modulated. Alternatively, or in addition, the time between pulses may be modulated to encode desired information. In some cases, a predefined sequence of communication pulses may represent a corresponding symbol (e.g. a logic "1" symbol, a logic "0" symbol, an ATP therapy trigger symbol, etc.). In some cases, conducted communication pulses may be voltage pulses, current pulses, biphasic voltage pulses, biphasic current pulses, or any other suitable electrical pulse as desired.

FIG. **4** depicts an illustrative medical device system **400**. For example, system **400** may include multiple devices that are implanted within a patient and are configured to sense physiological signals, determine occurrences of cardiac arrhythmias, and deliver electrical stimulation to treat detected cardiac arrhythmias. In some embodiments, the devices of system **400** may be configured to determine occurrences of dislodgment of one or more devices of system **400**. In FIG. **4**, an LCP **100** is shown fixed to the interior of the right ventricle of the heart **410**, and a pulse generator **406** is shown coupled to a lead **412** having one or more electrodes **408***a*-**408***c*. In some cases, pulse generator **406** may be part of a subcutaneous implantable cardioverter-defibrillator (SICD), and the one or more electrodes **408***a*-**408***c* may be positioned subcutaneously adjacent the heart. LCP **100** may communicate with the SICD, such as via communication pathway **308**. The locations of LCP **100**, pulse generator **406**, lead **412**, and electrodes **408***a*-*c* depicted in FIG. **4** are just exemplary. In other embodiments of system **400**, LCP **100** may be positioned in the left ventricle, right atrium, or left atrium of the heart, as desired. In still other embodiments, LCP **100** may be implanted externally adjacent to heart **410** or even remote from heart **410**.

Medical device system **400** may also include external support device **420**. External support device **420** can be used to perform functions such as device identification, device programming and/or transfer of real-time and/or stored data between devices using one or more of the communication techniques described herein, or other functions involving communication with one or more devices of system **400**. As one example, communication between external support device **420** and pulse generator **406** can be performed via a wireless mode, and communication between pulse generator **406** and LCP **100** can be performed via a conducted communication mode. In some embodiments, communication between LCP **100** and external support device **420** is accomplished by sending communication information through pulse generator **406**. However, in other embodiments, communication between the LCP **100** and external support device **420** may be via a communication module.

FIG. **4** only illustrates one example embodiment of a medical device system that may be configured to operate according to techniques disclosed herein. Other example medical device systems may include additional or different medical devices and/or configurations. For instance, other medical device systems that are suitable to operate according to techniques disclosed herein may include additional LCPs implanted within the heart. Another example medical device system may include a plurality of LCPs with or without other devices such as pulse generator **406**, with at least one LCP capable of delivering defibrillation therapy. Still another example may include one or more LCPs implanted along with a transvenous pacemaker and with or without an implanted SICD. In yet other embodiments, the configuration or placement of the medical devices, leads, and/or electrodes may be different from those depicted in FIG. **4**. Accordingly, it should be recognized that numerous other medical device systems, different from system **400** depicted in FIG. **4**, may be operated in accordance with techniques disclosed herein. As such, the embodiment shown in FIG. **4** should not be viewed as limiting in any way.

Implantable medical devices, such as LCP **100**, often have an energy storage module **112** with a limited power capacity.

The power capacity of the energy storage module **112** often dictates the useful life expectancy of the implantable medical device. In many cases, it is the pacing stimulation pulses delivered by the implantable medical device that dominate the energy consumption from the energy storage module **112**. As such, increasing the energy efficiency of the pacing stimulation pulses can increase the longevity of the energy storage module **112** and thus the implantable medical device, and/or may reduce the size (e.g., physical size and/or storage size) of the energy storage module **112** and thus reduce the size of the implantable medical device.

In some cases, implantable medical device may include a linear power regulator to convert the battery voltage produced by the energy storage module **112** (e.g. battery voltage) to another voltage used by the implantable medical device. For example, in some cases, an implantable medical device may have a battery voltage of 5 volts, but may deliver pacing pulses at a pacing amplitude of 2.5 volts. A linear power regulator may convert the 5 Volt battery voltage to the 2.5 volts uses in generating the pacing pulses. For a linear power regulator, the maximum efficiency of this conversion may be the ratio of the output voltage (2.5V) to the input voltage (5V), or in this case 50%. The conversion efficiency of other circuits for converting a battery voltage to another voltage are also less than idea. To overcome this inefficiency, it is contemplated that the pacing pulse amplitude may be set at or near the battery voltage, and the pulse width may be adjusted until pacing pulses are produced that reliably capture the heart.

FIG. **5** depicts a schematic flow diagram for an illustrative method **150** of pacing a heart with an LCP, such as LCP **100** of FIG. **1**. The illustrative method **150** includes identifying **152** a capture threshold for a pacing stimulation pulse delivered to a patient's heart, such as through two or more of the electrodes **114** and/or **114'** of the LCP **100**. The "capture threshold" may be identified by varying the pulse amplitude and/or pulse width until a stimulation pulse is found that just captures the heart.

The method **150** may further include delivering **154** a pacing stimulation pulse having a value for a first pacing pulse parameter (e.g., a pulse amplitude, a pulse width, and/or other parameter) and a value for a second pacing pulse parameter (e.g., a pulse amplitude, a pulse width, and/or other parameter) that are based, at least in part, on the identified capture threshold. In one example, the delivered pacing stimulation pulse may have a first pacing pulse parameter (pulse amplitude) and a second pacing pulse parameter (pulse width) that correspond to the capture threshold. In another example, the delivered pacing stimulation pulse may have a first pacing pulse parameter (pulse amplitude) and/or a second pacing pulse parameter (pulse width) that is a multiple of the parameters that correspond to the capture threshold, thereby providing a capture margin beyond the identified capture threshold. In another example, the delivered pacing stimulation pulse may have a first pacing pulse parameter (pulse amplitude) and a second pacing pulse parameter (pulse width) that is derived from a strength-duration curve that provides a capture margin beyond the identified capture threshold. These are just examples. In some cases, the pacing stimulation pulse may be delivered to a patient's heart from LCP **100** through the electrodes **114** and/or **144'** in response to a determination by the processing module **110** that a pacing stimulation pulse is needed or is to be initiated.

FIG. **6** depicts a schematic flow diagram of an illustrative method **160** for identifying capture threshold values. The illustrative method **160** includes setting **162** a first pacing pulse parameter to a fixed value (e.g., a fixed first value). In one example, the first pacing pulse parameter may be a pulse amplitude of the pacing stimulation pulse, and in some cases the fixed value may set at the battery voltage of the energy storage module **112** of LCP **100**. In some cases, the first fixed value may be considered "fixed" for at least a period of time.

Once the first pacing pulse parameter is set to the fixed value, the illustrative method **160** delivers **164** one or more pacing stimulation pulses to a patient's heart. In one example, the pacing stimulation pulses may be initiated by the processing module **110** of LCP **100**, generated by the pulse generator module **104**, and delivered through one or more of the electrodes **114** and/or **114'**. However, other pacing stimulation pulse delivery techniques may be utilized. While maintaining the first pacing pulse parameter at the fixed value, the illustrative method **160** may vary **166** the value of a second pacing pulse parameter (e.g. pulse width). In some cases, the value of the second pacing pulse parameter may be varied over different pacing pulses during a capture threshold test until the patient's heart is captured (e.g., as identified by the electrical sensing module **106** and/or the processing module **110**). The value of the second pacing pulse parameter may be varied in any manner including, but not limited to, varying the value of the second pacing pulse parameter on sequential pacing stimulation pulses of a group of pacing stimulation pulses, providing a first group of pacing stimulation pulses with a first value of the second pacing pulse parameter and then provide a next group (e.g., second or further group) of pacing stimulation pulses with a second value of the second pacing pulse parameter, and/or in any other suitable manner. Alternatively, the first pacing pulse parameter may be a pulse width of the pacing stimulation pulse and the pulse amplitude may be varied for two or more pacing stimulation pulses.

Once a capture threshold is identified from delivering pacing stimulation pulses, the illustrative method **160** may include identifying **168** a capture value for the second pacing pulse parameter. The capture value may correspond to the value of the second pacing pulse parameter used when the capture threshold is identified. In one example, where the second pacing pulse parameter is a pulse width, a value (e.g., a length of time) of the pulse width may be varied during the delivery of the one or more pacing stimulation pulses to identify a capture pulse width that corresponds to the capture threshold for the set fixed value of the first pacing pulse parameter (e.g., a set pulse amplitude). After identifying the capture threshold (e.g., the capture pulse width and the set pulse amplitude, or other values of the first and second pacing pulse parameters), the LCP **100** may deliver, via electrodes **114** and/or **114'**, one or more pacing pulses having values for the first pacing pulse parameter and the second pacing pulse parameter that is equal to or greater than the fixed value of the first pacing pulse parameter and/or equal to or greater than the capture value of the second pacing pulse parameter (e.g., see the delivering step **154** of method **150** in FIG. **5**).

In some cases, the processing module **110** of the LCP **100** may initiate identifying and/or may identify a capture threshold for a pacing pulse stimulation. In some case, the processing module **110** may initiate identifying and/or may identify a capture threshold at predetermined time intervals, after an identified event, after a patient changes position or posture, after a patient changes an activity level, and/or at one or more other times.

FIG. **7** depicts an illustrative strength-duration curve **170** with pulse duration (e.g., milliseconds (ms)) along the X-axis and pulse amplitude along the Y-axis. For all com-

binations of X values (e.g., pulse duration) and Y values (e.g., pulse amplitude) of a pacing stimulation pulse that fall on a particular strength-duration curve, a same or substantially the same stimulation effectiveness is provided by the pacing stimulation pulse to a patient's heart. As shown in the example of FIG. **7**, a pacing stimulation pulse at point A on the strength-duration curve **170** has a higher value for the first pacing pulse parameter (e.g., pace amplitude) and a lower value for the second pacing pulse parameter (e.g., pulse width) relative to the value of the first pacing pulse parameter and the value of the second pacing pulse parameter for a pacing stimulation pulse at point B. However, each of the pacing pulse parameter sets at point A and point B may provide the same or substantially the same stimulation effectiveness to the patient's heart (e.g. both will capture the heart similarly).

In some cases, one or more strength duration curves may be saved in a memory of the LCP **100** (e.g., memory of the processing module **110** and/or other memory) and/or in memory with which the LCP **100** may be in communication. In some cases, a family of strength-duration curves may be stored. The family of strength-duration curves may be based on the particular patient at hand, or on a population of patients. An illustrative family of strength-duration curves are shown in FIG. **8**. The LCP **100** may use an identified capture threshold for the particular patient, as determined through a capture threshold test performed by the implanted LCP **100**, to identify a particular one of the family of strength-duration curve that corresponds to the capture threshold for the particular patient. Once identified, the LCP may fix the pulse amplitude (e.g. at the battery voltage) and then pick the "nth" strength-duration curve to the right to identify the pulse width that provides an appropriate capture margin. The LCP may then pace the patient's heart using pacing pulses that have the fixed pulse amplitude (e.g. the battery voltage) and the pulse width that provides the appropriate capture margin.

In some cases, the LCP **100** may use one or more strength duration curves to adjust a value of a first pacing pulse parameter and/or a value of a second pacing pulse parameter while maintaining a stimulation effectiveness of the pacing pulses. In the example of FIG. **7**, point A may represent a pacing stimulation pulse at which a capture was identified and thus, the stimulation effectiveness at point A, and along the strength-duration curve **170**, may be considered the capture threshold. In some cases, the processing module **110** may determine that it is more power efficient to operate at a lower value of the first pacing pulse parameter and adjust the value of the second pacing pulse parameter to a value associated with the lower value of the first pacing pulse parameter along the strength-duration curve **170** (e.g., at point B on the strength-duration curve **170**). This may result in more efficiently provide pacing stimulation pulses while maintaining a stimulation effectiveness applied to the patient's heart by the pacing stimulation pulses. In some cases, a capture margin may be applied to the first pacing pulse parameter and/or the second pacing pulse parameter, as desired.

In one example, the processing module **110** may set (e.g., fix) the value of the first pacing pulse parameter to be equal to a power supply voltage provide by the energy storage module **112**, and may identify the pulse width at the capture threshold, and thus the strength-duration curve **170** that is associated with the capture threshold (e.g., where the strength-duration curve may be stored in memory associated with the LCP **100**). When the energy storage module **112** is a battery and the power supply voltage is the voltage of the battery, the voltage of the battery may decay over time. As a result, the value of the first pacing pulse parameter may also decay over time in proportion to the battery voltage decay. To account for the potential decay of the value of the first pacing pulse parameter, the processing module **110** may track the battery voltage, adjust the value of the first pacing pulse parameter as the battery voltage changes over time, and adjust a value of the second pacing pulse parameter (e.g. pacing pulse width) along the identified strength-duration curve **170** to points that correspond to the adjusted value of the first pacing pulse parameter to provide pacing stimulation pulse that provide the same or similar stimulation effectiveness. In some cases, a capture margin is applied to the second pacing pulse parameter to help ensure reliable capture of the heart going forward.

FIG. **8** depicts a plurality of strength-duration curves. As referred to above a family of strength-duration curves (e.g., the five strength-duration curves **170**, **172**, **174**, **176**, **178** depicted in FIG. **8**) may be saved in a memory of the LCP **100** (e.g., memory of the processing module **110** and/or other memory) and/or in memory with which the LCP **100** may be in communication. In some cases, the LCP **100** storing the family of strength-duration curves may facilitate the LCP **100** (e.g., the processing module **110**) provide pacing stimulation pulses in accordance with a received or identified capture margin. For example, a capture margin may correspond to a percentage offset of the capture threshold. When so provided, the capture margin may be higher when the capture threshold is higher. In another example, the capture margin may correspond to a fixed offset from the capture threshold. In yet another example, the capture margin may be selected by moving "n" strength-duration curve to the right in FIG. **8**, and then use the pulse amplitude and/or pulse width dictated by that strength-duration curve. These are just some examples.

In FIG. **8**, the strength-duration curve **170** may be considered to be associated with the capture threshold of the patient. That is the capture threshold identified via a capture threshold test falls along strength-duration curve **170**, such as at point A. The pacing stimulation pulses associated with each of the strength-duration curves **172**, **174**, **176**, and **178** to the right of the strength-duration curve **170** may provide a capture margin over the pacing stimulation pulses provided in accordance with the strength-duration curve **170**. In one example, the pacing stimulation pulses associated with each sequential strength duration curve **172**, **124**, **126** and **178** may provide one percent (1%) more, two percent (2%) more, three percent (3%) more, five percent (5%) more, ten percent (10%) more, twenty percent (20%) more, or any other suitable amount more pulse width than the pulse width provided by the pacing stimulation pulse associated with a strength duration curve **170**. In another example, the pacing stimulation pulses associated with each sequential strength duration curve **172**, **124**, **126** and **178** may provide one percent (1%) more, two percent (2%) more, three percent (3%) more, five percent (5%) more, ten percent (10%) more, twenty percent (20%) more, or any other suitable amount more pulse amplitude than the pulse amplitude provided by the pacing stimulation pulse associated with a strength duration curve **170**. In yet another example, the pacing stimulation pulses associated with each sequential strength-duration curve **172**, **124**, **126** and **178** may consume one percent (1%) more, two percent (2%) more, three percent (3%) more, five percent (5%) more, ten percent (10%) more, twenty percent (20%) more, or any other suitable amount of more power from the energy storage module **112** than the amount of power drawn by the pacing stimulation pulses

associated with a strength duration curve **170**. In another example, the pacing stimulation pulses associated with each sequential strength duration curve **172**, **124**, **126** and **178** may provide one percent (1%) more, two percent (2%) more, three percent (3%) more, five percent (5%) more, ten percent (10%) more, twenty percent (20%) more, or any other suitable amount more stimulation amount than the stimulation amount provided by the pacing stimulation pulse associated with a strength duration curve **170**. These are just examples. Moreover, rather than a linear progression from one strength-duration curve **172**, **124**, **126** and **178** to the next, it is contemplated that there may be a non-linear progression such as a step-wise progression, an exponential progression, a logarithmic progression, and/or any other suitable progression as desired.

In some cases, the processing module **110** of the LCP **100** may select a stored strength-duration curve based, at least in part, on an identified capture threshold and a predetermined capture margin and/or a capture margin received from a physician. In some cases, a capture threshold determined by a capture threshold test performed by the LCP **100** may not align directly with a stored strength-duration curve. In such cases, processing module **110** may select (e.g., automatically or upon selection and/or approval by a physician) a strength-duration curve that is closest to the capture threshold. Once the processing module **110** of the LCP has selected a strength-duration curve **170** associated with the capture threshold, the processing module **110** may identify a further strength-duration curve associated with the predetermined or received capture margin. For example, a capture margin may correspond to the "nth" strength-duration curve to the right of the strength-duration curve that is closest to the capture threshold.

In an example, the LCP **100** may fix the pulse amplitude (e.g. at the battery voltage) and then perform a capture threshold test by varying pulse amplitude. In FIG. **8**, this may correspond to point A along the strength-duration curve **170**. The LCP **100** may then pick the "nth" strength-duration curve to the right to identify the pulse width that provides an appropriate capture margin. For example, the LCP **100** may pick the first (e.g. n=1) strength-duration curve to the right **172**, and for the fixed pulse amplitude find a new pulse width at operating point C. Operating point C provides a desired pacing margin to help ensure reliable pacing going forward.

In another example, the LCP **100** may fix the pulse amplitude (e.g. at the battery voltage) and then perform a capture threshold test by varying pulse amplitude. In FIG. **8**, this may correspond to point B along the strength-duration curve **170**. The LCP **100** may then pick the "nth" strength-duration curve to the right to identify the pulse width that provides an appropriate capture margin. For example, the LCP **100** may pick the first (e.g. n=1) strength-duration curve to the right **172**, and for the fixed pulse amplitude find a new pulse width at operating point D. Operating point D provides a desired pacing margin to help ensure reliable pacing going forward. As shown in FIG. **8**, points A and C have the same pulse amplitude, but have different pulse widths to provide the desired capture margin. Likewise, points B and D have the same pulse amplitude, but have different pulse widths to provide the desired capture margin.

In some cased, and once a strength-duration curve has been selected to provide the desired capture margin, and the pacing amplitude drops over time due to a decreasing battery voltage, the processing module **110** may automatically adjust the pacing pulse width of the pacing stimulation pulses in accordance with the selected strength-duration curve. For example, assume the strength-duration curve **172** of FIG. **8** has been selected to provide the desired capture margin, and the initial pacing amplitude corresponded to point C. The processing module **110** may set the pacing pulse width to correspond to operating point C. As the batter drains over time, the pacing amplitude may drop down to point D. The processing module **110** may automatically drop the pacing pulse width over time along strength-duration curve **172** to operating point D, all along providing a desired capture margin and possibly without having to update the capture threshold.

In some cases, a physician may select a desired capture margin to use. A physician may take one or more factors into consideration when adjusting or selecting a capture margin for an LCP **100**. Some factors may include, but are not limited to, an absolute pulse amplitude margin (e.g. 2 volts), a relative pulse amplitude margin (+10%), an absolute pulse width margin (e.g. 50 ms), a relative pulse width margin (+10%), a pacing pulse energy margin (e.g. 10% more energy than at the capture threshold), a margin based on a desired lifetime of the LCP **100** and/or any other suitable margin. It is contemplated that a physician may select the capture margin using a user interface, such as user interface **180** shown in FIG. **9**.

In one example, the capture margin may be related to the estimated life (e.g., duration) of the LCP **100**. As such, a physician may be given an opportunity to select a Power Efficiency Value from a user interface **180** such as shown in FIG. **9**. Based on the Power Efficiency Value selected, an appropriate capture margin may be selected at which to use when providing pacing stimulation pulses. In some cases, a pulse amplitude/pulse width combination may be selected to achieve the selected Power Efficiency Value. In some cases, the particular pulse amplitude and/or pulse width may not be reported to the physician. Instead, the pulse amplitude and/or pulse width may be optimized to reduce the overall power consumption of the LCP **100**. For example, to minimize the energy consumed in converting a battery voltage to a different pacing pulse amplitude, the pulse amplitude may be set equal to the battery voltage, and the pulse width may be adjusted to achieve the desired capture margin. The capture margin may be dependent on the Power Efficiency Value selected by the physician.

The user interface **180** may be part of a remote device (e.g., external device **360**, external support device **420**, and/or a different remote device) that may be in communication with the LCP **100** over a network (e.g., communication pathway **308**). Alternatively, or in addition, the user interface **180** may be located in or on a personal computer, a laptop computer, a tablet computer, a mobile phone, a smart phone, and/or other computing device, wherein the selected value may be communicated to the LCP **100**.

As can be seen, the user interface **180** may include a Power Efficiency Value selector **182**. In the example shown, the Power Efficiency Value selector **182** may be a slide bar that may be slid between a minimum (min) value and a maximum (max) value. Additionally or alternatively, the Power Efficiency Value selector **182** may allow a user to select a specific value in a range of values, and the values may be for a generic range (e.g., 0-10, 0-100, 14-29, and so on), may be associated with an estimated life of the LCP **100** (e.g., in years), may be associated with a capture margin percent over a capture threshold, and/or may be associated with one or more other values. In some cases, the user interface **180** may include an indicator **184** (e.g., a dynamic indicator) of an estimated life for the LCP **100** based on (e.g., that changes with) a selected Power Efficiency Value. In one example, as a higher capture margin is selected via

the Power Efficiency Value selector **182**, the shorter the duration of the expected life remaining for the LCP **100**.

FIG. **10** is a flow diagram of an illustrative method **500** of setting values for parameters of a pacing stimulation pulse that may be related to an identified capture threshold. The method **500** may include the processing module **110** of an LCP **100** setting **502** a pace amplitude (note, pulse amplitude and pace amplitude may be used interchangeably herein) to a fixed pace amplitude. In one example, the fixed pace amplitude may be a power supply voltage (e.g. battery voltage) of an energy storage module **112**, a percentage of the power supply voltage, and/or other voltage. Then, while providing pacing stimulation pulses to a patient via the electrodes **114**, **114'**, the method **500** may include adjusting **504** a pulse width of the pacing stimulation pulses until a capture threshold has been identified, and then selecting **506** a threshold strength duration curve (e.g., curve **170** in FIGS. **7** and **8**) corresponding to the capture threshold.

As an alternative to setting the pace amplitude of the pacing stimulation pulses to a fixed pace amplitude and adjusting the pulse width of the pacing stimulation pulses to identify a capture threshold as in steps **502** and **504**, the processing module **110** may be configured to set the pulse width of the pacing stimulation pulses to a fixed pulse width and adjust the pace amplitude of the pacing stimulation pulses to identify a capture threshold.

At step **508**, the processing module **110** may determine whether a capture margin has been received, and if no capture margin has been received, the processing module **110** may set **510** electrical stimulation pulse settings based, at least in part, on the strength-duration curve corresponding to the capture threshold and a default capture margin if present. This may include automatically selecting a capture margin strength duration curve based, at least in part, on the default capture margin and the strength-duration curve corresponding to the identified capture threshold. Then, the processing module **110** may set **510** electrical stimulation pulse settings based, at least in part, on the selected margin strength-duration curve.

In instances when a capture margin has been received, such as from a physician, the processing module **110** may set electrical stimulation pulse settings based, at least in part, on the strength-duration curve corresponding to the capture threshold and the received capture margin. This may include automatically selecting **512** a capture margin strength duration curve based, at least in part, on the received capture margin and the strength-duration curve corresponding to the identified capture threshold. Then, the processing module **110** may set **514** electrical stimulation pulse settings based, at least in part, on the selected margin strength-duration curve.

FIG. **11** is a flow diagram of an illustrative method **600** of setting values for parameters of a pacing stimulation pulse that may be related to a capture threshold. In the illustrative method **600**, the processing module **110** may identify **602** a fixed pace amplitude. In one example, the fixed pace amplitude may be a power supply voltage (e.g. battery voltage) of an energy storage module **112**, a percentage of the power supply voltage, and/or other voltage. The processing module **110** may set **604** a pace amplitude of a pacing stimulation pulse to a fraction of the identified fixed pace. In one example, the set pace amplitude may be a fraction of a power supply voltage of the energy storage module **112**, and may be set based on a desired capture margin. In one example, if the capture margin is 2 times the capture threshold, the fraction may be set to one half and the set pacing amplitude will be one half of the identified fixed pace amplitude. Once the pace amplitude has been set and the while the LCP **100** may be applying pacing stimulation pulses to a patient, the processing module **110** may adjust **606** a pulse width of the pacing stimulation pulses until a capture threshold is identified. Once the capture threshold has been identified and an associated pulse width at the set pulse amplitude of the pacing stimulation pulse is stored, the processing module **110** may re-set **608** the pacing stimulation pulses to have the identified fixed pace amplitude and set **610** the pacing stimulation pulses to have the pulse width corresponding to that identified at the capture threshold. The resulting pacing stimulation pulse may have parameter values that result in the desired capture margin (2×).

In some cases, the processing module **110** may identify a strength-duration curve associated with the set pacing pulse parameter values that correspond to the capture threshold and the desired capture margin (e.g., the processing module **110** may select a strength-duration curve that may be the closest curve to the set pacing pulse parameter values) and adjust the pulse width over time as the pace amplitude changes over time due to power supply voltage decay or the like.

FIG. **12** is a flow diagram of an illustrative method **700** of adjusting, over time, a set pace amplitude for pacing stimulation pulses. The illustrative method **700** may be implemented by the processing module **110** of the LCP **100** at initial set up of the device before and/or after implantation, at pre-set intervals after initial set up of the implanted device, continuously in real-time after initial set up of the implanted device, and/or at any other time. The illustrative method **700** may include the processing module **110** determining **702** a fixed pace amplitude at which to set the pace amplitude of a pacing stimulation pulse, and determining **704** a pulse width at the fixed pace amplitude. As discussed herein, in one example, the fixed pace amplitude may correspond to the power supply voltage (e.g. battery voltage) of the energy storage module **112**, a percentage of the power supply voltage, and/or other voltage as desired. The pulse width at the fixed pace amplitude may be determined by identifying a pulse width associated with (e.g., lined up with) the fixed pace amplitude along a strength-duration curve (e.g., strength-duration curves **170**, **172**, **174**, **176**, **178** in FIG. **8** or other strength-duration curves). Once the fixed pace amplitude of the pacing stimulation pulses is determined **702** and an associated pulse width for the pacing simulation pulses is determined **704**, the processing module **110** may adjust **706** the electrical stimulation pulse settings to the determined fixed pace amplitude and the determined pulse width.

Over time (e.g., at pre-determined time intervals or in real time), the processing module **110** may determine **708** if a bases for determining the fixed pace amplitude has changed. In one example, if the fixed pace amplitude is set to be equal to a power supply voltage from the energy storage module **112**, the processing module **110** may determine if the power supply voltage from the energy storage module **112** has changed by a predetermined amount since the fixed pace amplitude was previously determined. This determination may be made continuously at pre-determined times and/or in real-time. If the processing module **110** determines the bases for determining the fixed pace amplitude has not changed, then the processing module **110** may maintain **710** the current pacing stimulation pulse settings and continuously determine **708** if a bases for determining the fixed pace amplitude has changed. If the processing module **110** determines the bases for determining the fixed pace amplitude has changed, then the processing module **110** may return to

determining **702** a fixed pace amplitude at which to set the pace amplitude of the pacing stimulation pulses and the method **700** may be repeated.

Those skilled in the art will recognize that the present disclosure may be manifested in a variety of forms other than the specific embodiments described and contemplated herein. For instance, as described herein, various embodiments include one or more modules described as performing various functions. However, other embodiments may include additional modules that split the described functions up over more modules than that described herein. Additionally, other embodiments may consolidate the described functions into fewer modules.

Although various features may have been described with respect to less than all embodiments, this disclosure contemplates that those features may be included on any embodiment. Further, although the embodiments described herein may have omitted some combinations of the various described features, this disclosure contemplates embodiments that include any combination of each described feature. Accordingly, departure in form and detail may be made without departing from the scope and spirit of the present disclosure as described in the appended claims.

What is claimed is:

1. A leadless cardiac pacemaker (LCP) for delivering pacing pulses to a heart of a patient, the LCP comprising:

a power supply for providing a power supply voltage;

a pair of electrodes for delivering pacing pulses to the heart of the patient;

a controller operably connected to the pair of electrodes and the power supply, the controller configured to:

identify a capture threshold by:

setting a pace amplitude to the power supply voltage;

delivering via the pair of electrodes a plurality of pacing pulses having the pace amplitude with different pulse widths to identity a capture pulse width that corresponds to the capture threshold of the heart;

deliver via the pair of electrodes a plurality of pacing pulses having the pace amplitude and a pacing pulse width that is greater than the capture pulse width by a pulse width margin.

2. The LCP of claim **1**, wherein the power supply comprises a battery, and the power supply voltage comprises a battery voltage provided by the battery.

3. The LCP of claim **2**, wherein the battery voltage, and thus the pace amplitude, decays over time.

4. The LCP of claim **3**, wherein the controller is configured to repeatedly identify the capture threshold.

5. The LCP of claim **1**, wherein the controller stores data representing one or more strength-duration curves, and the controller is configured to identify a capture threshold strength-duration curve based at least in part on the pace amplitude and the capture pulse width, and the controller is further configured to identify the pulse width margin by referencing a different one of the strength-duration curves and the pace amplitude.

6. The LCP of claim **5**, wherein if the power supply voltage changes, and thus the pace amplitude changes, the controller is configured to automatically adjust the pacing pulse width based at least in part on the different one of the strength-duration curves and the changed pace amplitude, without having to update the capture threshold by delivering via the pair of electrodes a plurality of pacing pulses having the changed pace amplitude and different pulse widths.

7. The LCP of claim **1**, wherein the controller is further configured to receive a user selectable power efficiency value, and wherein the pulse width margin is based at least in part on the user selectable power efficiency value.

8. A leadless cardiac pacemaker (LCP) for delivering pacing pulses to a heart of a patient, the LCP comprising:

a pair of electrodes for delivering pacing pulses to the heart of the patient;

a controller operably connected to the pair of electrodes, the controller configured to:

identify a capture threshold by delivering via the pair of electrodes a plurality of pacing pulses while varying a first pacing pulse parameter value while leaving a second pacing pulse parameter value fixed in order to identity a capture value for the first pacing pulse parameter; and

deliver via the pair of electrodes a plurality of pacing pulses that each have the first pacing pulse parameter value at the capture value and the second pacing pulse parameter value at a capture margin above the fixed second pacing pulse parameter value.

9. The LCP of claim **8**, wherein the first pacing pulse parameter is pulse width and the second pacing pulse parameter is pulse amplitude.

10. The LCP of claim **9**, further comprising a battery that provides a battery voltage, and wherein the fixed second pacing pulse parameter value is a predetermined fraction of the battery voltage.

11. The LCP of claim **10**, wherein the second pacing pulse parameter value at the capture margin above the fixed second pacing pulse parameter value corresponds to the battery voltage.

12. The LCP of claim **8**, wherein the first pacing pulse parameter is pulse amplitude and the second pacing pulse parameter is pulse width.

13. The LCP of claim **8**, wherein the controller stores data representing one or more strength-duration curves, and the controller is configured to identify the capture margin based at least in part on one or more of the strength-duration curves.

14. A leadless cardiac pacemaker (LCP) for delivering pacing pulses to a heart of a patient, the LCP comprising:

a pair of electrodes for delivering pacing pulses to the heart of the patient;

a controller operably connected to the pair of electrodes, the controller configured to:

receive a user selectable power efficiency value from a remote device;

identify a pulse width and pulse amplitude combination that corresponds to a capture threshold;

apply a capture margin to one or more of the pulse width and pulse amplitude resulting in a pacing pulse width and a pacing pulse amplitude, wherein the capture margin is based at least in part on the user selectable power efficiency value; and

deliver pacing pulses using the pacing pulse width and the pacing pulse amplitude.

15. The LCP of claim **14**, wherein the controller is configured to store data representing one or more strength-duration curves, and wherein the controller is configured to identify the capture margin by indexing the user selectable power efficiency value into the data representing one or more strength-duration curves.

16. The LCP of claim **15**, wherein the controller is configured to receive the data representing one or more strength-duration curves from the remote device.

17. The LCP of claim 14, wherein the remote device comprises a user interface including a display, wherein a user can use the user interface to select the user selectable power efficiency value.

18. The LCP of claim 17, wherein the remote device displays a slider on the display that allows the user select the user selectable power efficiency value from a range of allowable user selectable power efficiency values.

19. The LCP of claim 17, wherein the remote device displays a dynamic indicator of an expected life time of the LCP based, at least in part, on the user selectable power efficiency value.

20. The LCP of claim 14, further comprising a battery for providing a battery voltage, and wherein the pacing pulse amplitude is set to the battery voltage.

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